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6.—A new species of Eucalyptus from Western Australia

by F. D. Podger * and G. M. Chippendale †

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Abstract

A new species of *Eucalyptus* is described. The species, *E. laeliae* Podger et Chippendale, is closely related to the Powder Bark Wandoo, *E. accedens* W. V. Fitzg., and it occurs in some drainage lines of the Darling Scarp, associated with Jarrah, *E. marginata* Donn ex Sm..

Eucalyptus laeliae sp. nov. Arbor glabra, ad 20 m alta, cortice alba levi pulverea. Folia juvenilia 3-4 paribus, opposita ovata, deinde sub-opposita ovato-lanceolata. Folia matura alternata lanceolato-falcata coriacea, plerumque 10.0-16.5 cm longa et 1.4-2-2 cm lata (petiolo plerumque 1.1-1.6 cm longo incluso); nervi laterales ab utrinque parte costae medianae circiter 32-46 et cum ea angulum 40°-56° (plerumque 46°-54°) facientes. Umbellae axillares 6-9 florae (aliquando 4-11-florae), pedunculo 1.0-1.5 cm longo, subcompresso, margine incrassata, sursum dilatato; pedicelli 1.0-3.0 mm longi. Alabastri turbinato—obovoidei minute verrucosi, plerumque 6.5 mm longi; operculum hemisphaericum vel conicum, longitudine ½—2/3 tubi calycis qui plus minusve cylindricus 4.0-5.0 mm longus est. Antherae versatiles obovatae emarginatae rimis parallelis dehiscentes, glandula elliptica vel ovata. Fructus cupularo-cylindricus, minute verrucosus, plerumque 5.0-7.0 mm longus et 4.5-6.0 mm latus, margine angusta leviter convexa; semina subfusca irregularia plus minusve trigona, 1.0-1.5 mm longa. Cotyledones binati, segmentis anguste spathulatis.

Holotypus. 1.8 miles south east of North Dandalup on Whittakers Hill Road, about 43 miles south of Perth, Western Australia, 13/10/1966, L. McGann (FRI 13813). Isotypes at Perth, Sydney, Canberra and Melbourne.

Tree to 20 m high, with white, smooth powdery bark to the smallest branches, sometimes with older fragments of dark red-brown bark adhering; in autumn the newly exposed bark briefly butter-yellow. Young twigs somewhat quadrangular. Juvenile leaves opposite, ovate, for 3-4 pairs, then sub-opposite, ovate-lanceolate. Adult leaves alternate, lanceolate-falcate, coriaceous, mostly 10.0-16.5 cm long and 1.4-2.2 cm wide (including a petiole usually 1.1-1.6 cm long), with 32-46 pairs of primary lateral veins making an angle of 40°-56° (mostly 46°-54°) with the midrib. Umbels axillary, 6-9 flowered (occasionally 4-11 flowered). Peduncles 1.0-1.5 cm long, flattened, biconvex, thickened at margin, expanded towards top; pedicels 1.0-3.0 mm long. Buds turbinate-obovoid, minutely verrucose, mostly about 6.5 mm long; operculum 2.0-3.0 mm long hemispherical to conical, ½ to 2/3 as long as the calyx tube which is more or less cylindrical, 4.0-5.0 mm long. Anthers versatile, obovate, emarginate, opening in parallel slits; gland elliptical to ovate, nearly as long as the cells. Fruit cupular-cylindrical, minutely verrucose, mostly 5.0-7.0 mm long and 4.5-6.0 mm wide, clearly distinct from pedicel which is 1.0-2.5 mm long; rim narrow, slightly convex; disc included, convex; valves 3, rarely 4, deltoid, apiculate, shortly exsert. Seeds brown, irregular or roughly trigonal, rounded on back, 1.0-1.5 mm long. Cotyledons Y-shaped with the segments narrow spathulate.

Citation of specimens other than holotype. Western Australia: Helena River gorge, 2 miles south of Darlington, 3/9/1965, F.D. Podger (FRI 13808). 9 miles south east of Pinjarra on Pinjarra-Dwellingup Road, 24/8/1965, F.D. Podger (FRI 13807). 1.5 miles south east of Serpentine edge of Darling Range, 24/8/1965, F. D. Podger (FRI 13809). Mt. Cooke, 1.5 miles east of 43 mile peg, Albany Highway, 24/8/1965, F. D. Podger (FRI 13810). 7 miles east of Harvey on Harvey-Tallanalla Road, 15/7/1965, F. D. Podger (FRI 13811). Dirk Brook, near 37 mile peg, South Western Highway, 11/10/1966, G. Chippendale (FRI 13812). North Dandalup, 2/3/1967, L. McGann (FRI 14162).

Figure 3 A, C, D, E was drawn from the holotype, and B was drawn from FRI 14162.

E. laeliae (Figure 1) is confined to drainage lines of the Darling Range, near areas of exposed rock free of the lateritic mantle. It is not found on lateritic gravels. Generally, the species occurs in small pure stands, and where it is associated with *E. marginata* Donn ex Sm., *E. calophylla* R. Br. ex Lindl., *E. redunca* Schau. var. *elata* Benth., or, occasionally, *E. patens* Benth., it does not form an intimate mixture.

E. laeliae is clearly related to *E. accedens* W. V. Fitzg., but only occurs in the same area as the latter species at the Helena River locality, and even here it is half a mile distant. *E. laeliae* has consistently smaller buds and fruit, and usually three valves, while *E. accedens* usually has four valves. The powder on the

* Forest Research Institute, Kelmscott, Western Australia.

† Forest Research Institute, Canberra, Australian Capital Territory.

trunk of *E. laeliae* is white, while that on *E. accedens* is creamy with a pale orange tint. There is a tendency, only, for the new species to have more primary lateral veins at a slightly greater angle with the midrib than is the case in *E. accedens*. *E. laeliae* occurs only in drainage lines, whereas *E. accedens* occurs on lateritic gravels with a clay subsoil.

Figure 1.—*Eucalyptus laeliae* at Mt. Cooke.

Seedlings raised from the new species show no segregation of morphological characters. The seedling leaves of *E. laeliae* develop from narrow ovate to broad ovate, being opposite for at least six pairs and then subopposite, while in *E. accedens* seedling leaves develop to subrotund or parabolic and become distinctly alternate. (Figure 2.)

The species was previously confused with *E. accedens*. The specific epithet is a reference to Laelia, one of the vestal virgins, and thereby a reference to the white clothing of the tree.

Figure 2.—Seedling at ten weeks. A. *E. laeliae* (from F. D. Podger FRI 13807); B. *E. accedens* (from Mokine Brook near Wandering).

Acknowledgments

Thanks are due to the Directors of the State Herbaria for allowing one of us (G. C.) to examine collections of *Eucalyptus accedens*. The Latin description was kindly made by Dr. R. Storey, Division of Land Research, C.S.I.R.O., Canberra. Figure 3 was drawn by Miss Marjorie Hall, Forest Research Institute, Canberra.

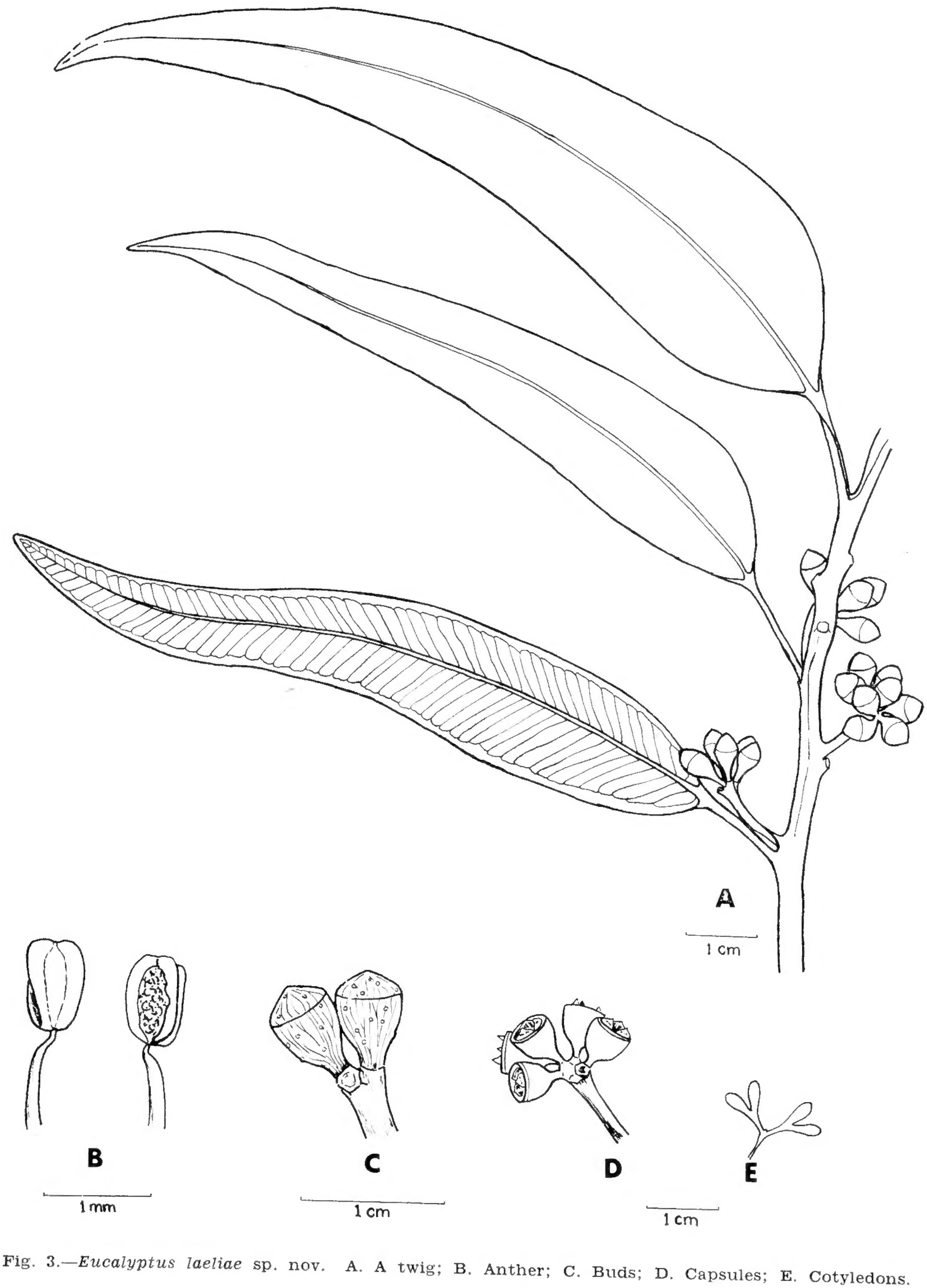

Fig. 3.—*Eucalyptus laeliae* sp. nov. A. A twig; B. Anther; C. Buds; D. Capsules; E. Cotyledons.

7.—Distribution and variation of the skink Ctenotus labillardieri (Gray) of southwestern Australia

by Julian Ford *

Manuscript received 20 June 1967; accepted in revised form 21 May 1968.

Abstract

This study of specimens in the Western Australian Museum collection has revealed the present distribution of *Ctenotus labillardieri* (Gray) to be restricted to the higher rainfall regions of South-Western Australia. The suggestion that it is also discontinuously distributed throughout more arid parts of the State has resulted from confusion with *C. lesueuri* (Duméril and Bibron). Geographic variation in several characters is discussed and the species is divided into two subspecies, *lancelini* subsp. nov. on Lancelin Island and the nominate form on the mainland and south coast islands.

Introduction

The skink *Ctenotus labillardieri* (Gray) inhabits the higher rainfall region of southwestern Australia. An assertion by Glauert (1960, 1961) in his revision of the family Scincidae in Western Australia that it also has a scattered and discontinuous distribution in the north-western and mid-western parts of Western Australia, prompted me to carry out an investigation on its distribution and variation. During this study specimens in the Western Australian Museum were examined including all of the material that was available to Glauert.

All northern records of *labillardieri* are attributable to misidentification of *C. lesueurii* (Duméril and Bibron), a species which is virtually allopatric with *labillardieri*. *C. lesueurii* occurs all over the State except the humid south-west corner although there is some penetration into the Swan coastal plain, the northern Darling Range and the south coast.

Confusion between *labillardieri* and *lesueurii* has arisen from the fact that, although the prefrontals are usually in contact in *lesueurii*, a small number of specimens have them separated as in *labillardieri*. Moreover, a number of these atypical *lesueurii* as well as individuals with normal head scalation resemble *labillardieri* in lacking a black, white-edged vertebral streak. However, *lesueurii* always has three supraoculars in contact with the frontal whereas in *labillardieri*, two are in contact except for a small percentage of south coast specimens which have three in contact.

Distribution and habitat preference

The range of *C. labillardieri* is the more humid parts of the South-West, north to Lancelin Island, east to Esperance and the Recherche Archipelago, and inland to Mundaring, Boddington, Woodanilling, the Stirling Range and Ravensthorpe. On the Swan coastal plain it is rare, having only been seen on the east side of Lake Clifton (in damp localities in Tuart, *Eucalyptus gomphocephala*, forest where there is considerable ground litter and fallen timber), and at Perth (Zoology Department, W.A. University). The specimens collected at the University (D. Bradshaw, pers, comm.) may have been transported there. There is possibly a distributional gap between Perth and Lancelin Island, where there exists a morphologically distinct population (Ford, 1963; 1965).

The species has a strong predilection for living under granite and gneiss and is particularly plentiful wherever these rocks are exposed in the Darling Range, Porongorup Range, lower South West corner and the extreme south coast; it is also found under fallen logs in these areas. In the Stirling Range it is fairly common on the higher more humid mountain slopes where slates are exposed.

East of Bremer Bay its distribution is possibly discontinuous and dependent on suitable rocky areas, known localities along this coastal strip including East Mt Barren, Kundip, Ravensthorpe (?), Esperance, Cape Le Grand and the lower Dalyup River. From the Recherche Archipelago it has been collected on Mondrain, Middle, Thomas, Charley and Figure of Eight Islands (Glauert, 1954), while in the vicinity of Albany it occurs on Bald, Michaelmas and Eclipse Islands.

It seems strange that *labillardieri* has not been found north of Mt. Helena in the Darling Range. It is quite abundant to the immediate south of its range limit so its scarcity or absence is doubtless real and probably related to slight changes in the nature of the terrain and climate. My belief is that likely habitats to the north become too dry during the summer since the species seems to prefer damp situations. The significance of the distribution gap between the Lancelin Island population and that on the mainland has been discussed elsewhere (Ford, 1963; 1965).

Taxonomy

Since the Lancelin Island population of *Ctenotus labillardieri* is clearly separable from all mainland and south coast island populations which may be grouped together, the following ternary nomenclature is proposed:

(1) *Ctenotus labillardieri labillardieri* (Gray)

Tiliqua labillardii J. E. Gray, 1839, Ann. Nat. Hist., 2: 289. Australia.

Lygosoma labillardieri Duméril and Bibron, 1839, Erpétologie générale 5: 73. Western Australia.

Hinulia greyii, J.E. Gray, 1845, Cat. Specimens Liz. Brit. Mus. p. 76 Swan River, Australia.

Ctenctus labillardieri Storr, 1964. W. Aust. Nat. 9: 44.

* Western Australian Institute of Technology, Bentley.

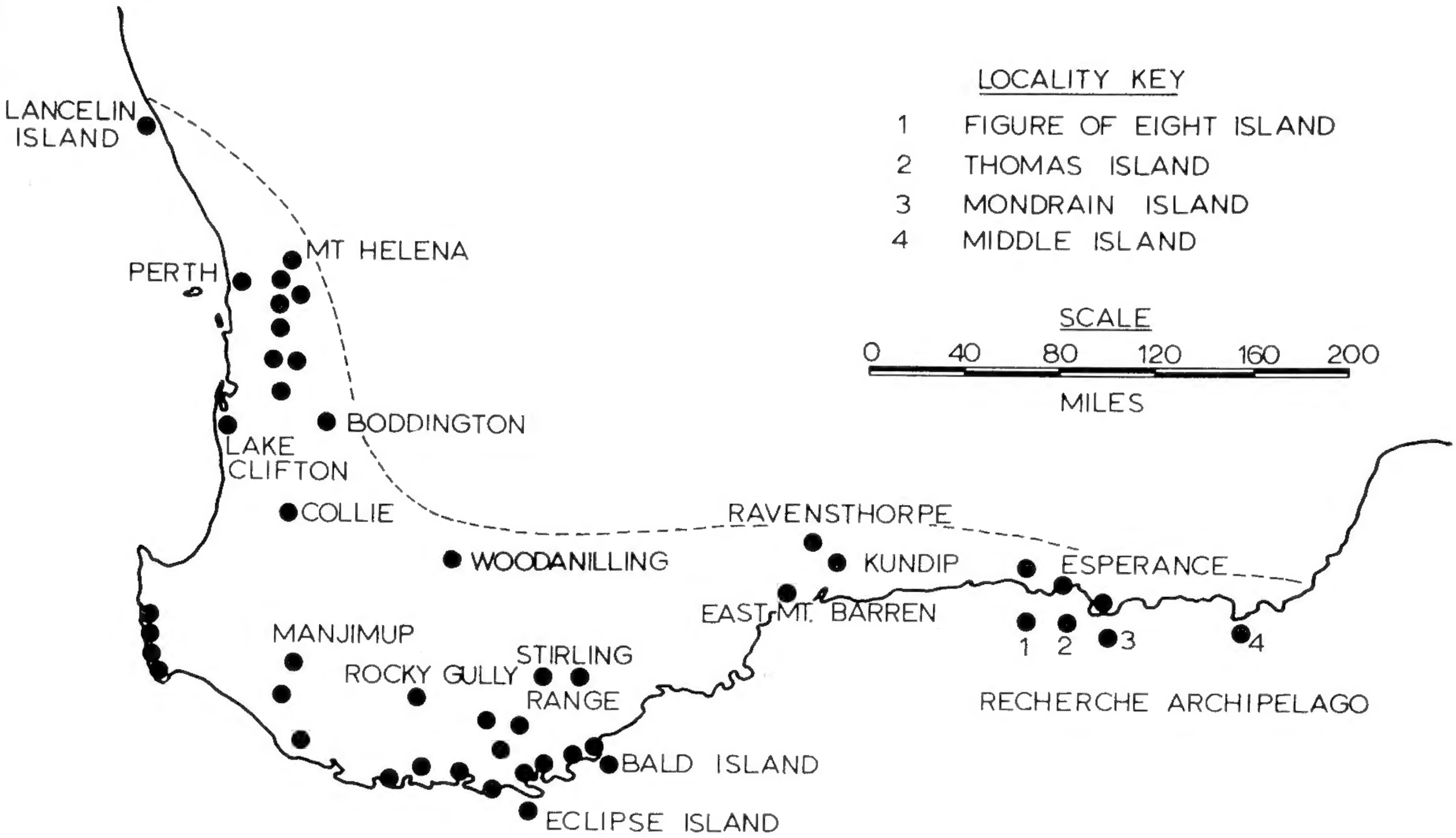

Figure 1—Map of the South-West of Western Australia showing location of specimens of *Ctenotus labillardieri*.

A variable dark form with the dorso-lateral white streaks contrasting sharply with the black streaks on the back and sides.

(2) *Ctenotus labillardieri lancelini* subsp. nov.

The holotype is R18872 (in the Western Australian Museum) collected by J. Ford on October 7, 1961, on Lancelin Island. The pale brown coloration, dappled appearance on the back, and yellow (instead of reddish brown) on the legs distinguishes this form from the nominate subspecies.

(3) *Ctenotus labillardieri* subsp.

Specimen R18005 collected on December 12, 1959, by G. M. Storr, 11 miles west of Ravensthorpe, may represent a new subspecies or may be an aberrant individual.

It is readily distinguished by its speckled appearance and by the dorso-lateral white lines being reduced to a series of pale dashes. Particulars of the specimen are—head plus body length 50 mm; midbody scales 26; upper labials 7+7; ear lobules 5+4; lamellae under fourth toe 21; ratio hind leg to fore 1.39. There are three supraoculars in contact with the frontal on one side, and two on the other; the interparietal is small and narrow instead of being about the same size as each of the frontoparientals, which in this specimen are of unequal size.

Included in the material identified by Glauert as *C. labillardieri* is an undescribed species represented by specimen R10639 collected at Dumbleyung and which has since been collected at Boyagin (R22516-7). It and *C. labillardieri* can be considered sibling species.

Geographic variation

Coloration

Although nominate *labillardieri* may be divided into a number of fairly distinct colour types, geographic variation in colour pattern tends to be clinal. There is also a certain amount of individual variation, particularly in south-coast populations.

The population from the northern part of the Darling Range between Boddington and Mt. Helena is characterised by sharply defined markings on the back and sides. The dorsal surface is usually bronze-brown. A narrow white sharp-edged streak starts on the supra-oculars and runs dorso-laterally down to the tail where it becomes less distinct. Bordering on the dorsal side of this is a fine black streak of similar sharpness, and below (starting behind the eye) a broad black streak which is frequently spotted with white and pale brown. This in turn is bounded below by a mid-lateral narrow white streak which commences below the eye and passes through the ear and over the limbs to the tail; it is somewhat ragged-edged compared with the dorso-lateral white streak. Below this is another fairly broad black-brown streak followed by a third ragged-edged white streak starting below the ear aperture and passing almost ventro-laterally through the limbs. The dark markings on the sides below this are of irregular shape and tend to form a narrow ventro-lateral brown streak between the limbs. The under surface is whitish except on the chin and throat where the scales have small brown flecks. Two juvenile specimens from Lake Clifton are identical with Darling Range material

except that the back is silvery grey with minute black flecking; the upper surface of their limbs are orange with small irregularly shaped black markings which are not interconnected.

In the extreme South-West corner, the markings are less sharp, particularly on the sides. The back is not bronzy but varies between olive-brown and a bright pale brown, and it sometimes has faint black flecks. The dorsal black streaks are slightly broader and have a single row of pale spots. The white mid-lateral streak is almost zigzag-shaped and there is merely a resemblance of the ventro-lateral white streak because of the almost complete absence of dark markings below it. The upper lateral black zone is irresgularly spotted and the lower dark area has a speckled appearance. On the legs the black markings are bold and form a network.

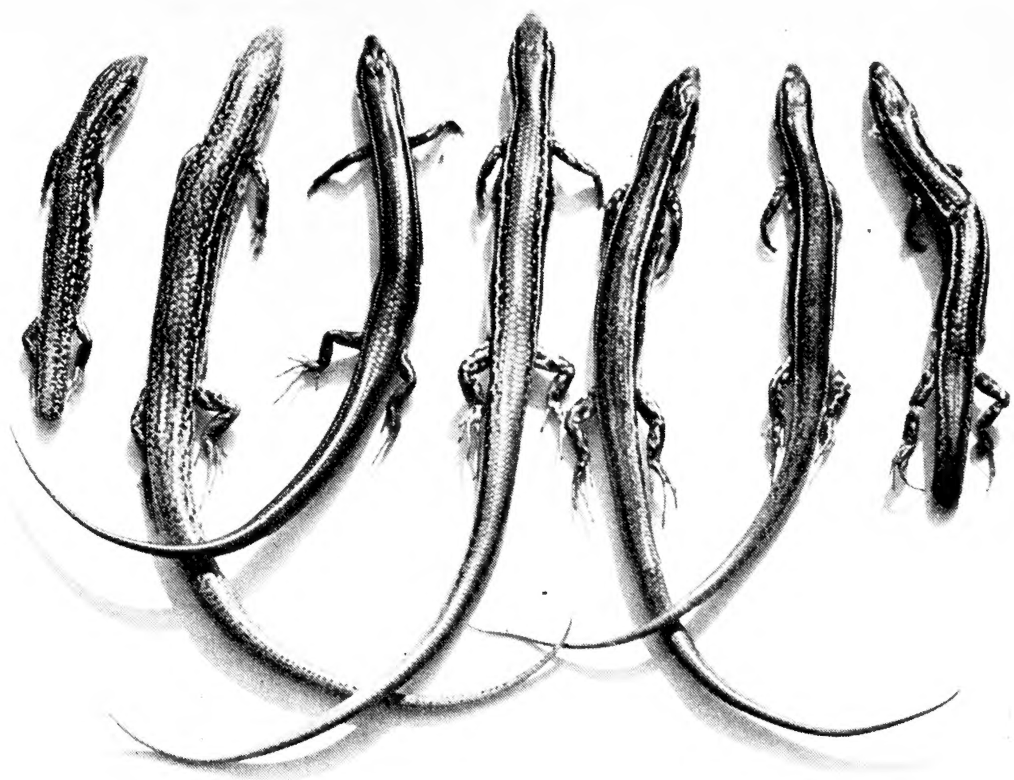

Figure 2—Specimens of *C. labillardieri* from left to right are from Ravensthorpe, Lancelin Island, Mundaring, Northcliffe, Bald Island, Mt. Many Peaks and the lower Dalyup River.

Material from the south end of the Darling Range is intermediate between that from the lower South-West and the north Darling Range area, there being a smooth transition from one form to the other although the gradient appears to be steep.

Along the extreme south coast, between Northcliffe and Mt. Many Peaks, the black and white streaked pattern on the sides remains virtually constant but the amount of black on the dorsal surface appears to increase from west to east, and the black dorsal streaks become broader and more ragged-edged. Both the dorsal and upper lateral black streaks are white spotted as in South-West specimens. There are also blackish dashes on the back which tend to form a line down the centre, and in some cases, two indistinct black lines. This trend is developed further in the populations on Bald and Eclipse Islands where most specimens have a ragged-edged black vertebral streak from the nape to behind the hind limbs so that there is much less brown dorsally.

The Porongorup Range, Mt. Barker and Rocky Gully material is like that from the deep South-West except that the black streaks are slightly broader and more ragged-edged, and there are longer fine blackish flecks on the back which varies in colour between brown and bright pale brown. The dorso-lateral white streak is slightly ragged. The mid-lateral white streak is zigzag-shaped or disjointed while the brown below is very irregular giving the sides a speckled appearance. Stirling Range material is like that from the Porongorup Range except that the vertebral brown area on the back is broader due to narrower black streaks, while the side pattern is still more speckled in appearance with the black reduced.

East of Bremer Bay the species is possibly split into a number of disconnected populations which has resulted in each being different morphologically. Mostly however, the various populations resemble lizards from Mt. Many Peaks in that the outer dorsal black streaks are broad but differ in being sharper edged. Specimens from the lower Dalyup River, Esperance and Cape Le Grand have this pattern but the material from the last locality does not have any spotting on the outer dorsal black streaks.

The East Mt. Barren specimen has rather narrow outer dorsal black streaks like those from the lower South-West corner, and the vertebral area is silvery brown rather than brown as in other specimens from this coastal strip.

Unfortunately only single specimens are available from Middle, Mondrain, Thomas and Figure of Eight Islands in the Recherche Archipelago, and each is slightly different. The example from Figure of Eight Island (see Glauert, 1954) is similar to Eclipse and Bald Island specimens in having an irregular vertebral black streak and ragged-edged outer dorsal black streaks. The Thomas Island specimen is practically identical with specimens from Cape Le Grand, while the Middle Island and Mondrain Island specimens are similar to those from the south coast between Albany and Denmark although there is no spotting on the outer dorsal black streaks and there is a tendency towards the formation of a middle streak down the back.

Lancelin Island specimens are very distinctive since their pale brown (instead of dark brown and black) colouration gives them a washed-out appearance. The pale streaks are like those in south coast specimens in not being sharp-edged and are not distinct on the head and behind the hind limb. On the upper dorsolateral

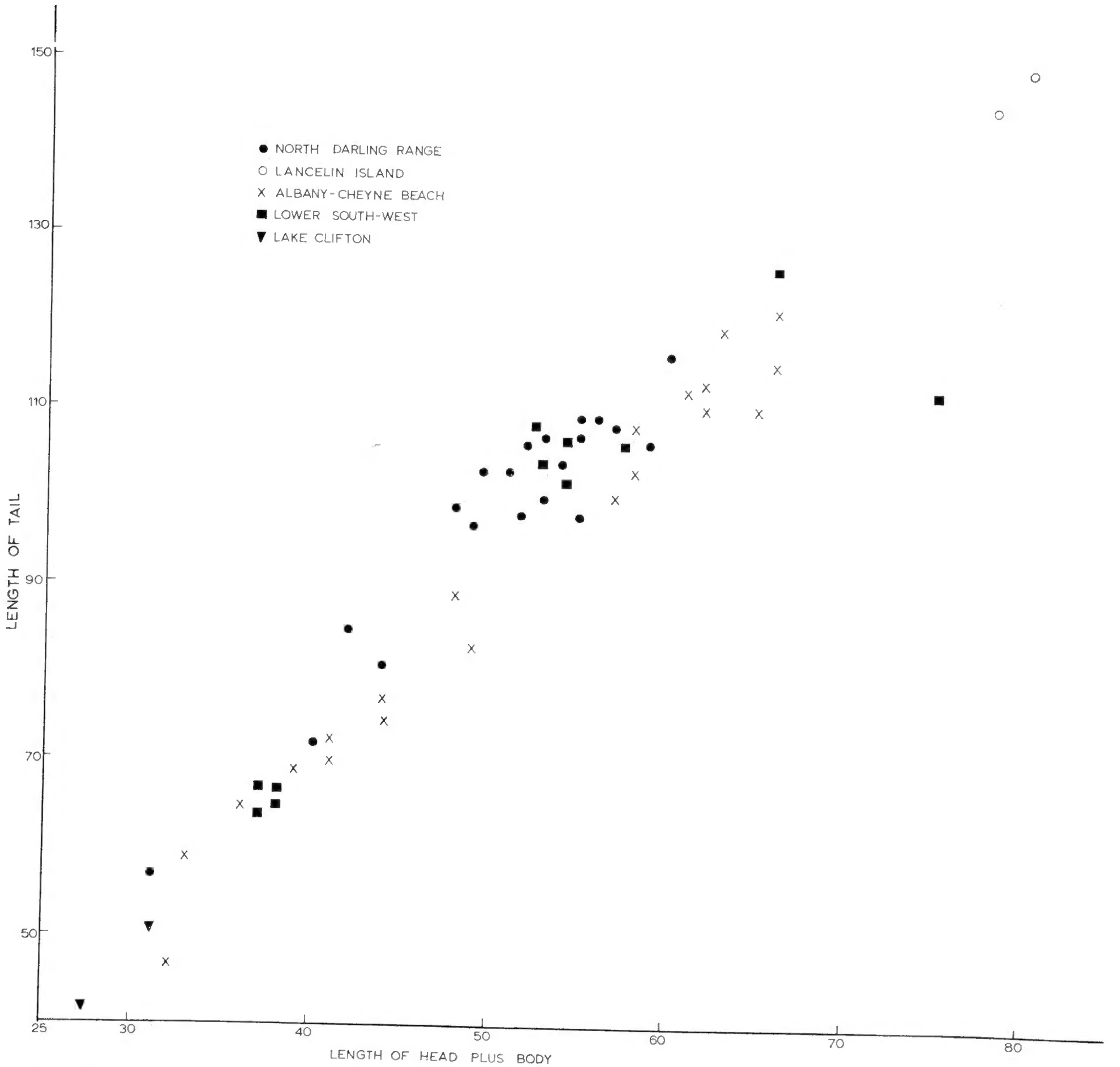

Figure 3—Graph showing relation between length of tail and head plus body of populations of *C. labillardieri*.

dark brown streak there is a series of pale dashes, and the dark areas below are relatively pale and irregularly marked lighter. On the back is a network of dark brown dashes connected with the poorly defined outer dorsal dark brown streaks which are broken up with somewhat enlarged spots. There is only a little flecking on the head and throat. As in mainland populations, the abdomen is a bright yellow during the breeding season. The dark markings on the upper surface of the limbs are also reduced.

The only specimen from Ravensthorpe has a distinct black and grey speckled appearance and does not resemble any other specimen. The dorsolateral white streak is discontinuous, merely consisting of a series of white dashes. The outer dorsal and upper lateral black streaks commence at the eye, are both ragged edged, and have grey spotting. There is no median lateral pale streak, the lower half of the sides being irregularly marked white and dark grey. On the grey back is a liberal peppering of small black spots which extend on to the head as two fine lines producing a stippled appearance. Small black spots are also distributed in rows on the upper limbs.

Trends in coloration

From the south-west corner northwards there is a definite tendency for the longitudinal streaks to become narrower and sharper, a trend which reaches its peak in the northern part of the Darling Range. The Lancelin Island population does not carry on this cline and constitutes a morphologically distinct isolate. Along the south coast the black dorsal streaks are broader and ragged-edged or spotted.

Between Cape Naturaliste and King George Sound an increase in the amount of black pigmentation on the back appears to be clinal. East of King George Sound the amount of black pigmentation of the black remains more or less constant. On some of the islands along the south coast, including Eclipse, Bald, and Figure of Eight Islands, the trend for melanisation is developed a stage further with the formation of a vertebral black streak.

In the eastern part of its range (east of Albany) there appears to be a south-north cline of slightly increasing degree of speckleness on the sides; in the Ravensthorpe specimen the back is speckled too.

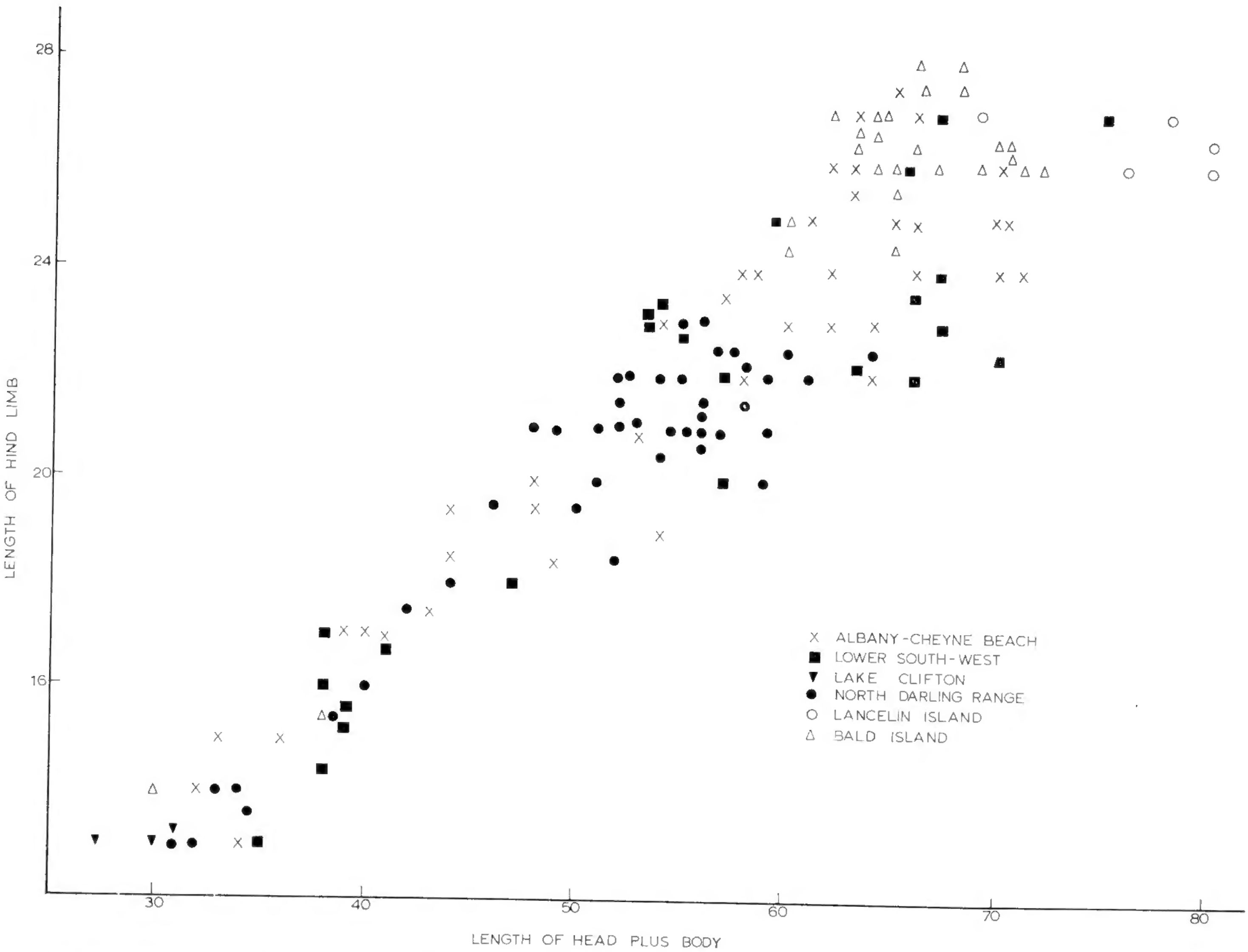

Figure 4—Graph showing relation between the length of the hind leg to the head plus body of populations of *C. labillardieri.*

Measurements and meristics

Several clines in measurements and meristics are indicated in Table 1. There appears to be north-south clines of decreasing magnitude of the tail length to head plus body ratio, of decreasing number of mid-body scales, and of decreasing number of upper liabials. Similar clines appear to exist in *Egernia pulchra* Werner and *E. bos* Storr (Ford, 1963). These trends in *labillardieri* may possibly exist in an east-west direction but the material from the species' range east of Bremer Bay is insufficient for any definite conclusions to be made. The Bald Island population has a relatively high mean number of mid-body scales and ear lobules and the data suggest that other island populations on the south coast may share this characteristic. The hind-leg length to fore-leg ratio shows virtually no geographical and, as would be expected for a non-burrowing skink, age variation. Table 1 shows that variation in the hind-leg length to the head plus body ratio is indicated but this is not geographically significant and is associated with allometric growth as illustrated by Figure 4. That allometry is very slight in the growth of the tail with respect to the head plus body can be seen from Figure 3.

TABLE 1

Mean measurements and meristics of Ctenotus labillardieri, *with standard deviations in brackets*

Locality	Sample Size*	Head + Body Length (mm)	Ratio, Tail Length to Head + Body	Ratio, Hind-leg to Head + Body	Mid-body Scales	Upper Labials	Ear Lobules	Lamellae under fourth Toe	Ratio, Hind-leg to Fore-leg
Lancelin Island	5† (2)	76.6 (4.2)	1.86 (0.05)	0.35 (0.03)	24 (0)	8 (0)	3.60 (0.61)	23.00 (0.71)	1.58 (0.03)
Perth-Lake Clifton	3 (2)	29.3 (2.9)	1.62 (0.09)	0.44 (0.03)	25 (0)	7 (0)	3.33 (0.60)	24 (0)	1.59 (0.05)
North Darling Range	44 (20)	51.3 (8.6)	1.94 (0.09)	0.39 (0.02)	25.80 (1.24)	7.61 (0.50)	3.32 (0.68)	23.80 (1.70)	1.53 (0.06)
South Darling Range ..	4 (0)	60.0 (4.3)	...	0.39 (0.03)	26.00 (1.63)	7.25 (0.62)	3.75 (0.95)	23.25 (1.70)	1.57 (0.03)
Lower South West	24 (11)	54.3 (4.7)	1.84 (0.10)	0.39 (0.04)	26.46 (1.02)	7.31 (.049)	3.45 (0.63)	22.84 (1.70)	1.54 (0.09)
Manjimup-Denmark .	21 (7)	57.7 (6.0)	1.78 (0.08)	0.40 (0.04)	27.19 (1.34)	7.25 (0.45)	3.60 (0.68)	24.40 (2.39)	1.55 (0.07)
Albany-Cheyne Beach .	40 (22)	55.6 (11.8)	1.76 (0.08)	0.40 (0.03)	26.35 (1.13)	7.31 (0.47)	3.73 (0.66)	24.12 (1.84)	1.52 (0.08)
Stirling Range	7 (2)	55.8 (5.3)	2.04 (0.33)	0.37 (0.04)	26.00 (1.00)	7.33 (0.50)	3.63 (0.74)	24.00 (0.94)	1.53 (0.09)
Bald Island .	27 (0)	62.4 (4.0)	...	0.41 (0.02)	29.30 (1.04)	7.41 (0.50)	3.93 (0.62)	24.74 (1.97)	1.54 (0.05)
Eclipse Island	1	53	..	0.43	30	8	4	23	1.48
Figure of Eight I	1	73	..	0.39	26	8	4.5	23	1.60
Thomas Island	1	...	.	..	28	8	4	25	1.53
Mondrain Island	2	62	..	0.45	28	8	4	27	1.60 (0.02)
Middle Island ..	1	75	..	0.37	29	8	4	25	1.56
Bremer-Esperance	4 (1)	55.3 (4.5)	1.62	0.40 (0.04)	26	7.80 (0.45)	4.5 (0.58)	22.50 (3.11)	1.55 (1.10)

* The figure in brackets is the number of specimens with a complete tail.

† All juveniles

About 10% of specimens from the south coast east of Northcliffe have three supraoculars in contact with the frontal instead of two, and there is possibly a west-east cline in the frequency in this character. Glauert (1954) noted that the specimen from Figure of Eight Island has three supraoculars in contact with the frontal, but in his key (1960, 1961) he ignores this and states that the frontal is always in contact with two supraoculars. Only one Bald Island specimen (out of 24) and three Cheyne Beach specimens (out of 23) have three supraoculars adjoining the frontal. The single Ravensthorpe specimen has three contacting the frontal on only one side.

TABLE 2

Specimens of C. labillardieri *grouped according to number of mid-body scales, upper labials and ear lobules*

Population	Mid-body scales				Upper labials		Ear lobules			
	24 25	26–27	28 29	30–32	7	8	2	3	4	5
Lancelin	5	0	0	0	0	5	0	2	3	0
Mainland northern	19	24	5	0	22	31	4	27	20	1
Mainland southern	24	89	31	0	73	38	1	69	72	10
Bald and Eclipse Islands	0	1	18	13	19	14	0	7	21	4

Discussion

The study of the adaptive nature of certain geographic trends in the morphology of reptiles has just begun (Mayr, 1963, p. 325). North-south clines and radial clines from the south-west corner in certain bird-species in South-western Australia are correlated with the climatic gradients of temperature and humidity (Ford, in prep.) and this may well be so in several lizard species. In the case of *Ctenotus labillardieri, Egernia pulchra* and *Egernia bos*, clines in meristics and body proportions are in the same direction for each species and coincide with the temperature gradient, indicating that physiological factors may be involved.

That at least some of the variation in colour pattern in *C. labillardieri* is an expression of climatic adaption is indicated by the increased black pigmentation in the south, particularly on several islands along the south coast where the climate is cooler. Kramer (1949) found that lizards on small rocky islands in the Mediterranean tended to be melanistic, the oldest islands among islands of equal size having the blackest forms. The increased melanization, which has a polygenic basis, helps the lizards to warm up during cool seasons and in the morning (Mertens, 1952).

The occurrence of similarly coloured populations on three widely separated south-coast islands (Bald, Eclipse and Figure of Eight), distinct from that on the adjacent mainland, may have arisen in three different ways, viz. (1) parallel evolution resulting from similar selection pressures and adaptation to similar ecological and climatic conditions; (2) the isolation of the remnants of a form which was once distributed on the mainland where it has now disappeared; or (3) the gradient of the north-south cline of increasing melanisation being steeper between the mainland and the islands because of the isolation and concomitant breakdown of gene flow.

The reduction in the amount of dark pigment in *lancelini* is possibly an edaphic adaptation involving cryptic coloration against the substrate as a result of predation by birds (Ford, 1963). It is also possible that the paleness is correlated with the mild climate of this small island where lizards find it less difficult to warm up than their fellows in cooler areas.

The larger size of specimens from Lancelin Island may be due in some way to their belonging to the northernmost population. G. M. Storr (pers. comm.) informs me that at least two other skinks, *Ctenotus lesueurii* and *Sphenomorphus monotropis* (= *richardsoni*), and several *Amphibolurus* species increase in size from south to north. It could be that large size in an adaptation for conserving body water (Schmidt-Nielsen, 1964): with increasing length, relative surface area decreases (and relative evaporative loss).

Specimens examined

R18871-5 (Lancelin Island); R1978-9 (Mt. Helena); R8850, R21229 (Mundaring); R14858 (Mundaring Weir); R4907-8 (Herne Hill); R19120, R19492-4 (Kalamunda); R4676 (Gooseberry Hill); R10262-4 (Barton's Mill); R3340-1, R5984-6, R21262 (Darlington); R627 (Glen Forrest); R4965 (Gosnells); R17987-8, R19118 (Karragullen); R17990 (Roleystone); R17981-2 (Churchman's Brook); R19247, R19803 (Byford); R17985-6 (Wongong Brook); R17992-5 (Keysbrook); R17977, R17978-80 (Serpentine Dam); R6768 (Banksia Dale); R10708-10 (Boddington); R17966-8 (Lake Clifton); R19244-6, R17969 (Collie); R17953-5 (Margarent River); R13446 (Karridale); R259, R263, R12783, R17956-65 (Cape Leeuwin); R66 (Mammoth Cave); R19833, R13417 (Boranup); R12426, R12776 (Deepdene); R5578-9, R8184, R19039-40, R17950, R5582 (Manjimup); R5580-1 (Pemberton); R17970-3 (Mt. Chudalup); R11039 (Nornalup); R260-1, R264 (Kent River); R19853-4 Denmark); R17952 (Rocky Gully); R21823 (West Cape Howe); R10946 (Albany); R4251, R4514 (Chorkerup); R18004 (Pardalup); R19117 (Lower Kalgan River); R7732 (Calgardup); R6571 (Woodanilling); R21809-15 (Mt. Toolbrunnup, Stirling Range); R21805-8 (Devil's Slide, Porongorup Range); R17872-6 (Mt. Many Peaks); R17926-47, R21819 (Cheyne Beach and lower Waychinicup River); R17877 (Waychinicup River); R11005 (Kundip); R17976 (East Mt. Barren); R17949 (lower Dalyup River); R14948 (Esperance); R17901 (Mondrain Island); R10234 (Thomas Island); R8684 (Middle Island); R22529 (Cape Le Grand); R17903-20, R179021-5, R19972-4 (Bald Island); R11278 (Eclipse Island); R10119 (Figure of Eight Island); R18005 (Ravensthorpe).

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8.—Further recoveries of two impact-fragmented Western Australian meteorites, Haig and Mount Egerton

by W. H. Cleverly*

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Abstract

The site of find of the Haig octahedrite iron meteorite has been revisited, an impact pit of unusual type recognised 183 m distant, and 23.3 kg of fragments recovered. Consideration of the pit, distribution of material, and its impact damage, enable a reconstruction of the circumstances of fall and fragmentation. The mineralogy is briefly noted.

The site of the unique Mount Egerton meteorite has been relocated. More than 3000 fragments resulting from severe impact fragmentation and weighing 27 kg have been recovered. The morphology of the material is described and the proportions of enstatite and metal assessed. The meteorite is grouped with Shallowater as an unbrecciated, metal-bearing (21%) enstatite achondrite.

THE HAIG METEORITE

Introduction

The main mass of the Haig octahedrite iron weighing c. 480 kg was discovered in 1951 by A. J. and H. E. Carlisle, who later donated it to the Western Australian Museum. The site of find (Fig. 1) is nearer to Rawlinna than to Haig and has approximate coordinates 31° 23' S., 125° 38' E.

* School of Mines of Western Australia, Kalgoorlie.

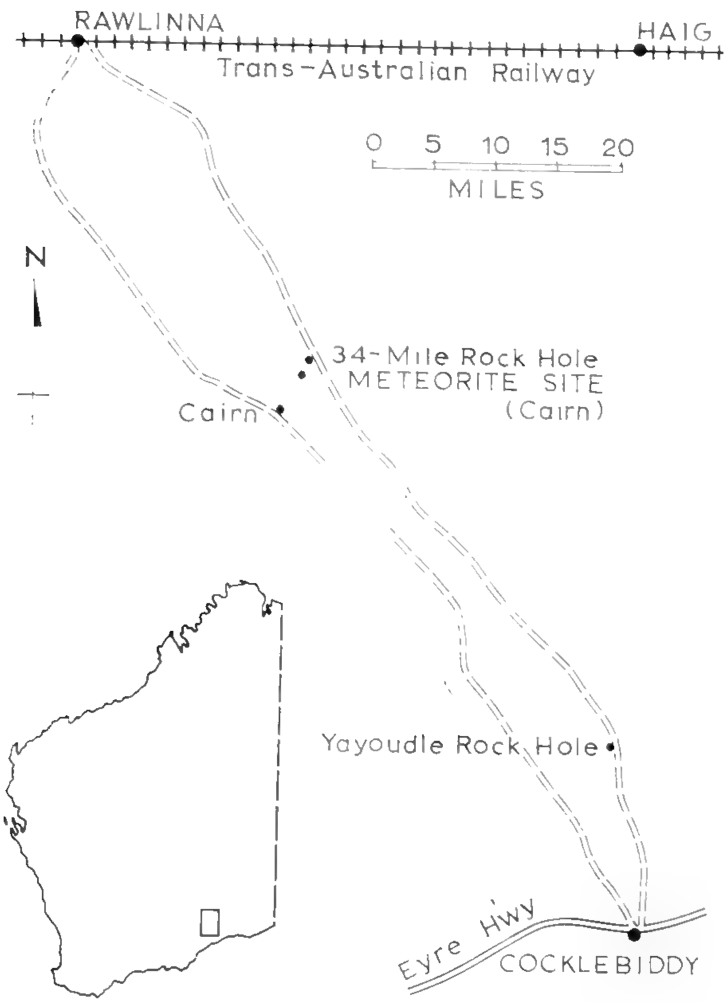

Figure 1.—Location of Haig meteorite recovery.

In 1965, A. J. Carlisle guided M. K. Quartermaine and the writer to the site to seek fragments whose existence had been predicted from fracture scars on the main mass. During the search, Mr. Carlisle noted a shallow pit 183 m south of the site with limestone fragments of sub-travertine type on its northern side. Correctly interpreting this inconspicuous pit as of impact origin (though the area abounds with sink holes and allied features), he walked the line towards the site of the main mass and found the major fragment of 22.88 kg almost immediately. Minor fragments were also recovered, and the pit was later excavated.

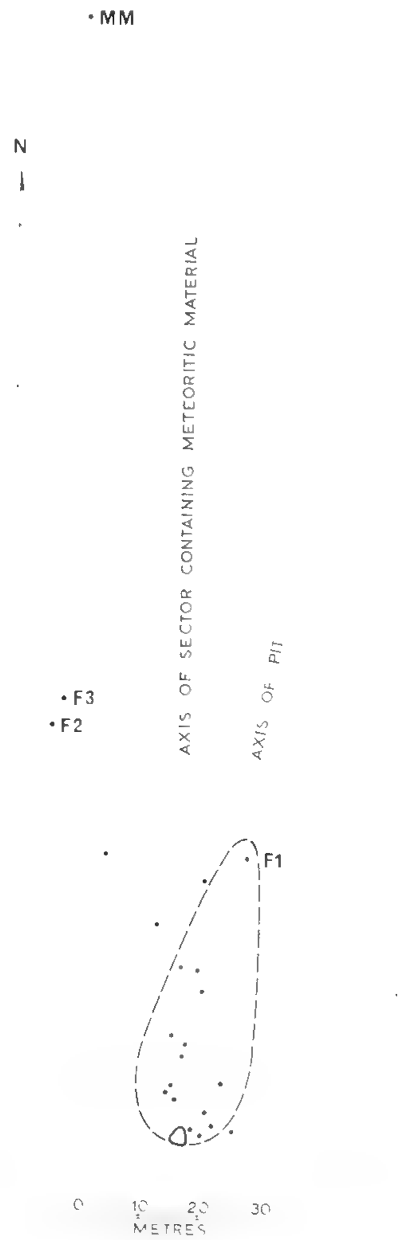

Figure 2.—Field distribution of the main mass (MM), major fragments (F1-F3), and minor fragments (indicated by dots) of the Haig meteorite relative to its impact pit. Limestone fragments ejected from the pit are enclosed within the broken line.

The fragments, of aggregate weight 23.27 kg, are in the collection of the Geology Department, School of Mines, Kalgoorlie. Reconstruction is almost complete, and the original weight of the mass was therefore close to 504 kilograms.

Field occurrence

Minor fragments (less than 20 g), major fragments, and the main mass were distributed in that general sequence from the impact pit (Figs. 2 and 3).

Figure 3.—Impact pit of the Haig meteorite partially excavated, looking north (compare with Figure 2). The vehicle (left of centre, near skyline) is at the site of the main mass; the small cairn (right, middle distance) is on the site of fragment 1 and the standing figures at the site of the other two large fragments. Most minor fragments were within the triangle formed by the pit, cairn and standing figure. Limestone fragments from the pit are less prominent than outcropping limestone and boulders, except in the area immediately beyond the pit.

The main mass was not seen in situ but must have lain much as it is now displayed in the Western Australian Museum (McCall and de Laeter 1965, Pl. VI A), and lightly embedded. Fragment 1, which is narrow and sharply keeled, had one end of the sharp edge embedded 16 cm into the soil, and much of its fracture surface had lost detail by rusting. The remaining fragments lay flatly on the surface or shallowly embedded.

In plan view, the impact pit has the shape of an isosceles triangle with blunted corners, and thus resembles the anterior face of the meteorite (Figs. 4 and 5), but the pit is more than four times larger in dimensions and higher in proportion to its base. The depth was 10 to 20 cm and the floor relatively flat except for a gentle transverse roll or shallowing approximately coincident with its widest part in a west-east direction (Fig. 10 F). The fill of angular limestone fragments (40 cm thick in the centre of the pit) graded in depth through fractured slabby limestone into bedrock. More than 1.6 m^3 of limestone fragments form a narrow, flame-shaped area of dispersion, the density of distribution declining rapidly from the pit; a similar volume of fragments remained within the pit.

Morphology of meteoritic material

Main mass.—This has dimensions 71.5 x 67 x 37 cm and the general shape of a bluntly tapered wedge which is widest where it is thinnest. Except on the weathered posterior face and the major fracture scars, the surface has a number of gentle rolls and hollows and well developed regmaglypts. The regmaglypts are polygonal, equidimensional, and 2-4 cm wide except in a pronounced zone of elongation and parallelism on the anterior face (Fig. 5)—where large individuals measure 9.1 x 3 cm and 7.6 x 5.1 cm—and in a less pronounced zone on the right-hand side of flight. The average length to width ratio of aligned regmaglypts on the anterior face is 2.0, but the effect is absent within hollows ("grouped regmaglypts").

Impact damage is present as scars, splayed or sheared corners and edges (including the rims of regmaglypts), from which small waves of metal are turned parallel to the general surface or even overturned. The directions of damage are thus indicated, and are confirmed by the disposition of undamaged hollows and the high points which shadowed them. The damage shows that the mass plunged into the ground with that face termed anterior directed

forward (upward damage on apical face, steeply upward parallel to regmaglypts on right side, detachment of major fragments posteriorly in a direction normal to the anterior face as discussed below); it continued to move forward and to "dive" downward with the apex directed forward (outward shearing of entire edge of apical face, damage directed towards heel on right-hand side), at the same time rotating slightly anticlockwise (damage wrapping on to heel from right-hand side and directed to left of heel on anterior face); finally, it overturned (almost completely reversed damage on the leading right-hand face, the other faces shadowed or lifting).

The large scar on the left side (Fig. 7), has a rough angular surface except along its posterior margin, where there is a slightly concave, sheared fringe of variable width. Fragment 1 fits closely except along this fringe, where the concavities present on both main mass and fragment combine to form a gap opening posteriorly to 1.4 cm wide. Fragment 2 fits similarly on a small adjacent scar with a posterior gap 0.6 cm wide.

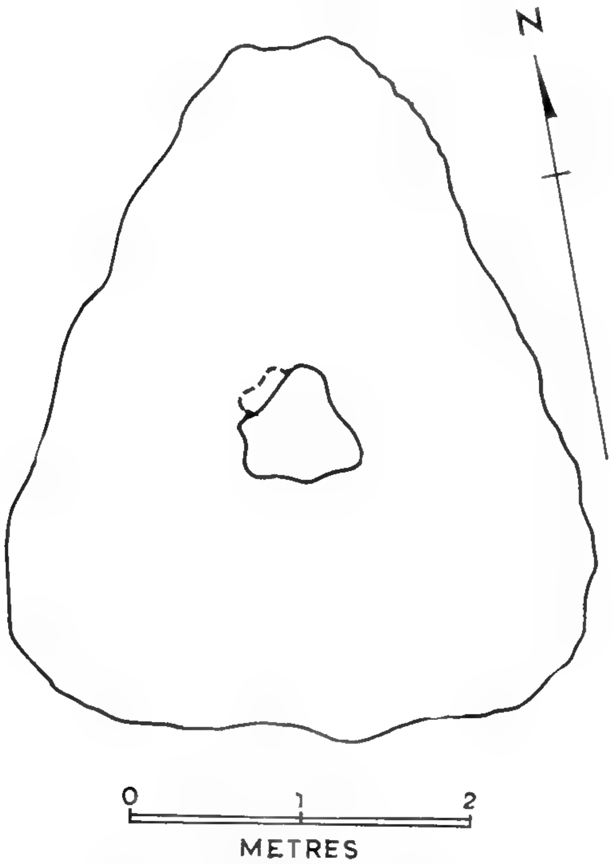

Figure 4.—Outline of Haig meteorite impact pit with superimposed outline of anterior face of the meteorite (face down). Fragment 1 is restored to position (broken line).

Major fragments.—Fragment 1 measures 30 x 23.5 x 14 cm and has the same surface features and directional damage as the adjoining areas of the main mass. Damage is severe on the anterior face and particularly on the outer edge which is splayed over in places as far as 15 millimetres. In restored position, this damaged edge is 7 cm above the general level of the anterior face and was thus its leading edge.

Fragment 2, of weight 163.1 g, is an irregular slab measuring 7 x 5 cm and about 1 cm thick. One face shows regmaglypts; the other has a pattern of equilateral triangles and angular projections, and is therefore octahedral. The marginal sheared fringe is represented by a small triangular area 1 cm wide at the base and showing the usual concavity. Fragment 3 of 38.1g is essentially similar except in its smaller size.

Minor fragments.—These show a variety of forms dependent on their origins.

(a) Five of the smallest, of weights 0.8-1.3 g, are thin and ragged, and may have a flattened and highly sheared face. They are deflected edges of the meteorite sheared to the point of detachment. The longitudinal section of one such fragment, cut perpendicular to the sheared face (Fig. 6) has a laminated structure resembling inverted, truncated, current bedding, and having some analogies with that structure in consisting of superimposed layers of stripped material, the meteorite and the earlier layers contributing to the later ones. The metal is finely granular and without trace of Widmanstätten texture.

(b) Eight fragments, of weights 0.6-15.8 g, have original surface except on a single sheared face. They appear to have been detached from upstanding edges as a result of one or two momentary blows rather than by a sustained shearing contact. Two of the fragments show also a partially exposed internal shear plane.

(c) Two thoroughly angular fragments of weights 0.9 g and 4.9 g have their shape defined by octahedral partings, and could have been plucked from the main fracture surface. A fragment of 3.6 g is similar except in having some original surface, and it could therefore have come from the anterior edge of the fracture surface. Likewise a fragment of 6.6 g with one sheared face, but otherwise octahedral, could have originated from the sheared fringe.

(d) A flattened fragment of 6.2 g has clearly been highly compressed. Both faces are strongly sheared and a third, internal, parallel shear is partially exposed. This is the type of fragment visualized as having been ejected from the notches along the posterior edges of the main fractures in a manner to be described below.

Fracture surfaces

Crystallographic interpretation.—The fracture scars show clearly the influence of Widmanstätten texture except on their sheared fringes. With few exceptions (resulting from distortion), the structure lines on the main scar (Fig. 7) comprise four sets in 45° relationship, and arise from fracturing generally parallel to a cube plane of the taenite, modified in detail by octahedral parting. The "north-south" and "west-east" lines of the central and flatter portion of the scar are the usual pattern for the cubic section of an octahedrite; the other less prominent lines, also at right angles and bisecting the angles between the first pair, are present only upon octahedral partings and are an equilateral triangular pattern projected upon the cube plane.

The ideal situation is shown with the same orientation in Figure 8. Octahedral planes

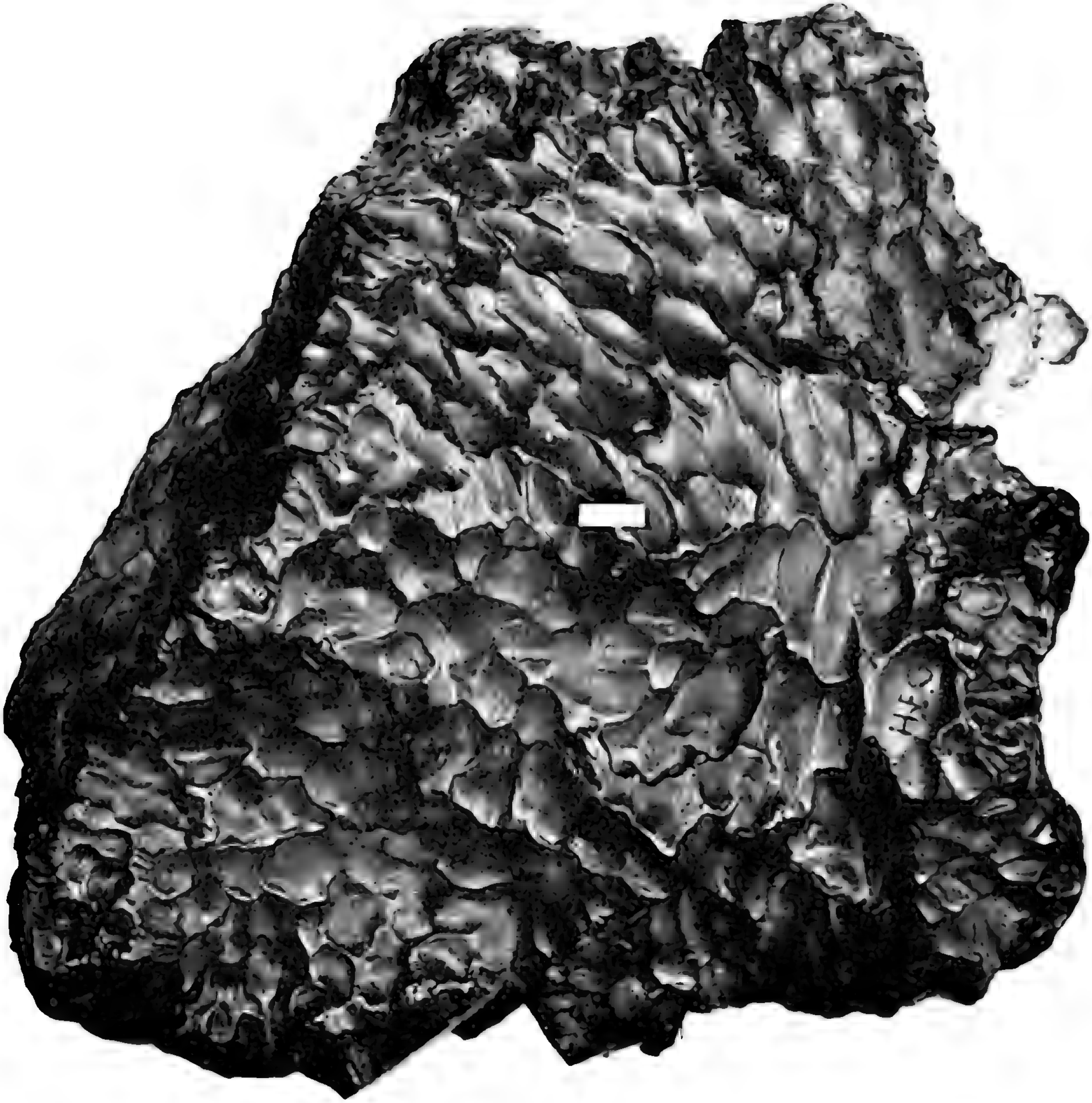

Figure 5.—Anterior face of the Haig meteorite with fragment 1 restored to position, apical end upward and heel at the bottom. The apex pointed in the direction of flight, and as this view is of the underside of the mass, the left hand side of flight is on the right of the figure and vice versa. Note severe impact damage on leading edge (top right).

appear on the cube face as lines parallel to the intersections of the two forms (the edges of the cube face); they appear on other octahedral faces as lines parallel to edges of the octahedron.

Small, square-based, pyramidal or wedge-shaped projections from the fracture surface were formed by octahedral parting and have the form of one half of an octahedron. Angular projections from the larger octahedral partings, such as the scar of fragment 2 (lower left of Fig. 7), have the form of equilateral-triangular pyramids, one parting being the base, the other three the faces.

Mechanical interpretation.—The rough angular area of the main fracture indicates brittle

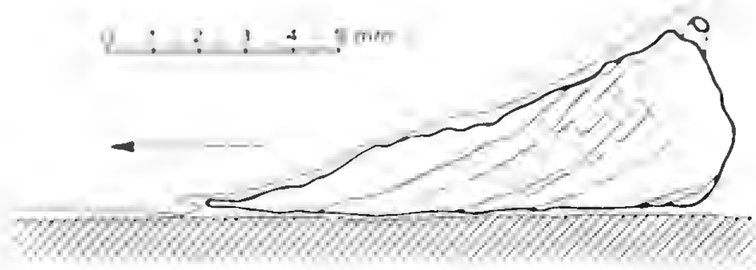

Figure 6.—Longitudinal section of a minor fragment of the Haig meteorite showing superimposed laminae of metal stripped from the meteorite and supposed relationship to the meteorite at the moment of detachment. The apparently isolated tip belongs to a curled layer not fully in the plane of the section.

tensional failure. As the anterior face of the meteorite met the ground, the prominent leading edge of fragment 1 would be hinged violently outward (a tensional effect), the detaching fragment retaining contact momentarily along its posterior hinge. Thereafter, the simplest explanation would be that the detaching fragment moved (relatively) upwards as both main mass and fragment plunged deeper into the limestone. Slickensides on the sheared fringes would then be in opposed directions and the sheared surfaces either relatively flat, or at least complementary in shape (Fig. 9A). The preferred explanation involves a combination of brittle and ductile behaviour in the manner of failure of a concrete beam (Fig. 9B). As a tensional fracture extends upward from the lower face, the neutral axis rises and compression is increasingly concentrated upon a rapidly shrinking area of cross-section. Material is "exploded" from the compressed hinge in a ductile manner of failure. The slickensides on both surfaces are then upward, and loss of material results in a notch.

The shearing on the main mass is upward but that on the margins of the major fragments cannot be interpreted with confidence. However, the existence of notches is incontrovertible, and the opposed sides, far from being complementary in shape, are almost mirror images (Fig. 9C). Their combined shapes are reminiscent of a line of greatest normal stress in a beam, and the "beaked" profiles of fragments 1 and 2 suggest that metal has been dragged upward and outwardly turned.

The two mechanisms are not entirely exclusive, but the relatively upward movement of the fragments probably occurred without contact being maintained at the hinge. Significantly, the shape of the pit resembles that of the meteorite more closely if fragment 1 is not restored to position (Fig. 4).

Localisation of the major fracture depended upon a fortuitous combination of factors including the downwardly projecting outer edge, the deep embayment in the side of the main mass (Fig. 5), and the smaller embayment at the apical end (now considerably enlarged by

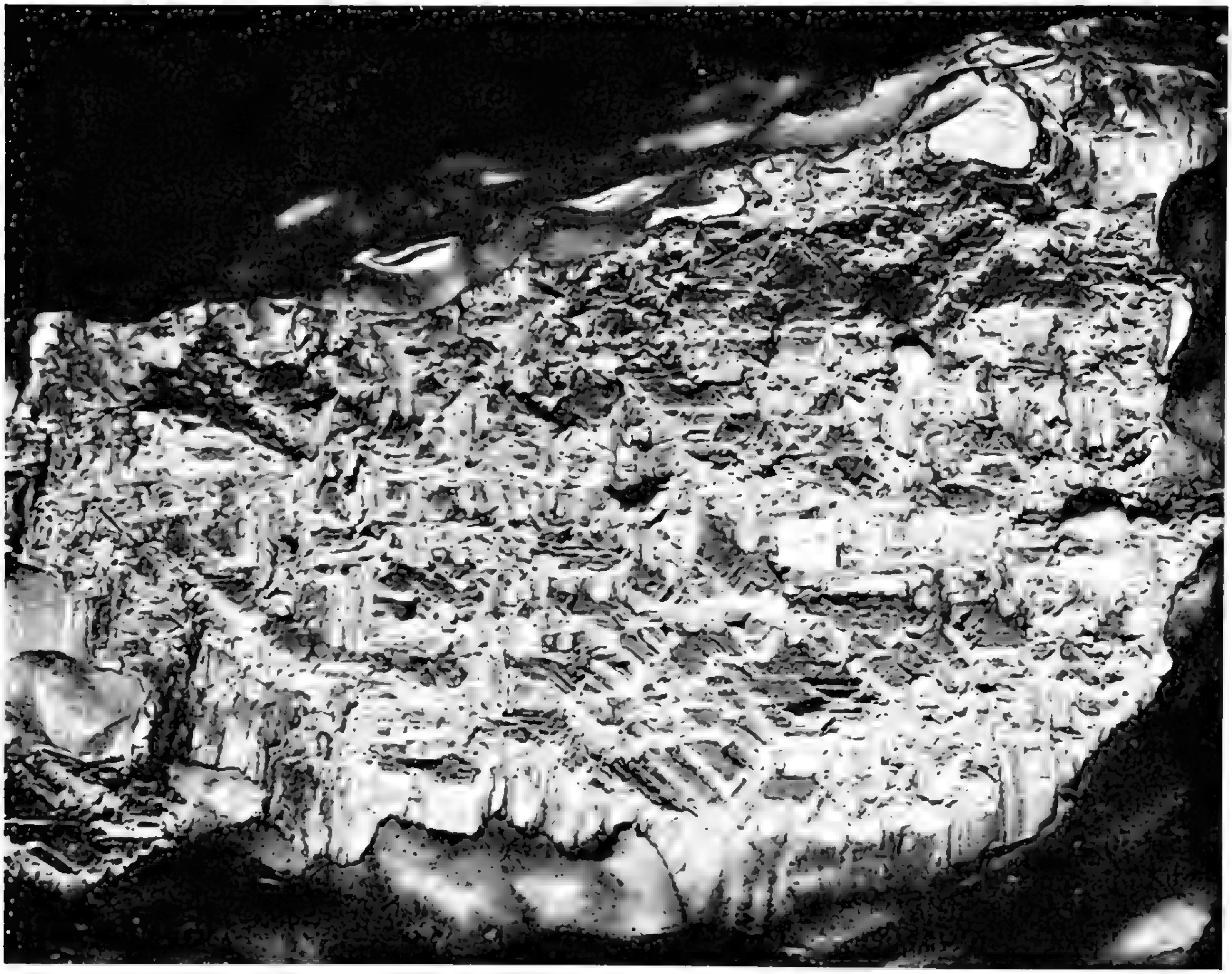

Figure 7.—Fracture scar of fragment 1 on the main mass of the Haig meteorite generally parallel to a cube plane of the taenite, but modified by octahedral parting. A concave, strongly sheared hinge area along the lower (posterior) margin. Two cavities resulting from loss of a nodular constituent towards upper right. The smaller scar of fragment 2 at extreme lower left has the pattern of equilateral triangles of an octahedral parting, here seen obliquely. A small fragment has been cut from the mass at top right.

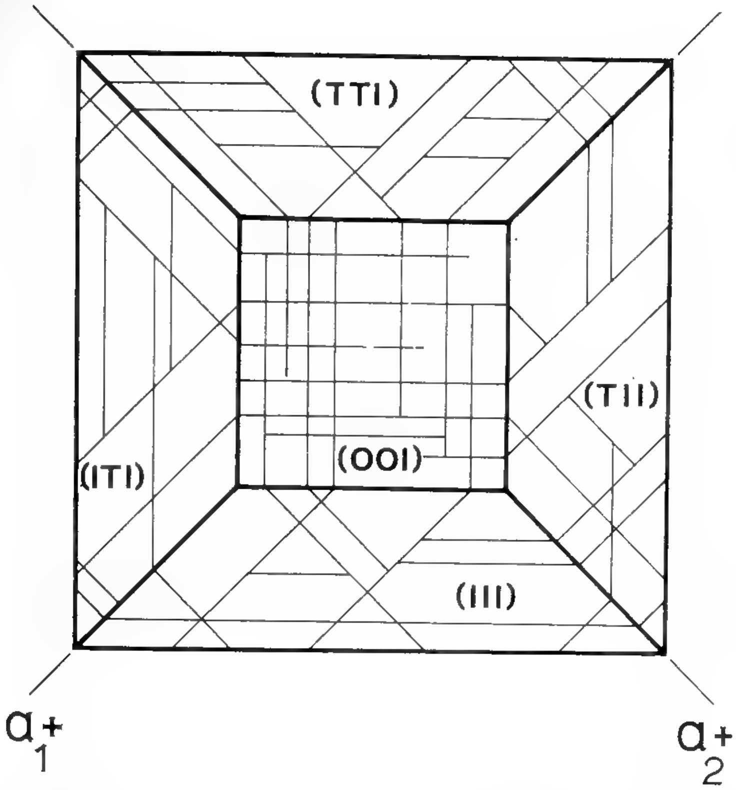

Figure 8.—View down the a_3-axis of a taenite octahedron modified by the cube face (001), showing the overall pattern of four sets of lines in 45° relation to each other resulting from octahedral sets of kamacite plates.

octahedral parting from fragment 1 and shearing on the main mass). Stress would be concentrated at such notches and they also made possible a short fracture path.

Aspects of the fall and fragmentation

Velocity.—A meteorite weighing 504 kg will reach terminal velocity within the earth's atmosphere and continue in free fall (Heide 1964, Tables 3-6). From data supplied, Dr. D. E. Gault (private communication) has calculated that the impact velocity would be of the order of 500 metres per second.

After impact, the main mass travelled on for a further 183 metres. The minimum velocity requirement is 42 m/s for a single arc of flight of 45° elevation. For flatter angles (or for the complementary, but unlikely steeper angles) higher velocities are necessary, but at flatter angles there is increased probability that the mass would ricochet or bounce and roll. Thus, for example, a velocity of 60 m/s is needed for a flight of 10° elevation and two-thirds distance, but the mass would probably continue on for the full distance. It is likely that the velocity immediately after leaving the pit need not have exceeded 60 metres per second.

If the velocity was reduced from 500 m/s to 60 m/s at the pit, more than 98% of the kinetic energy was consumed. Even if the interval between the velocities is drastically narrowed by halving the one velocity and doubling the other, the figure is still greater than 75%. This is consistent with the observation that damage to the meteorite is explainable in terms of a single event, and that no ground damage other than the pit was detected.

Orientation.—For purposes of discussion, an arbitrary angle of trajectory of 45° is used (Fig. 10A-F).

Orientations with the centre of mass above the fulcrum provided by the apex of the mass may be disregarded. Cases A and B tend to penetration rather than rebound unless the angle of trajectory is improbably low; neither are the major fragments detached in a direction normal to the anterior face ("hinges" are parallel to the anterior face). In case C, the fragments might be correctly detached but only at high trajectory where there is no tendency to continued forward movement. Case D is favoured because it could result in a "heel and toe" action which fits the sequence of events deduced from impact damage, provides a possible explanation for the shallow transverse roll in the floor of the pit, and at the same time could give the mass a forward velocity. The shape of the mass is ideally suited because of the wide bearing surface at the base of the anterior face and the relative narrowness of the apical end. As the anterior face moved forward into a horizontal position, the major fragments

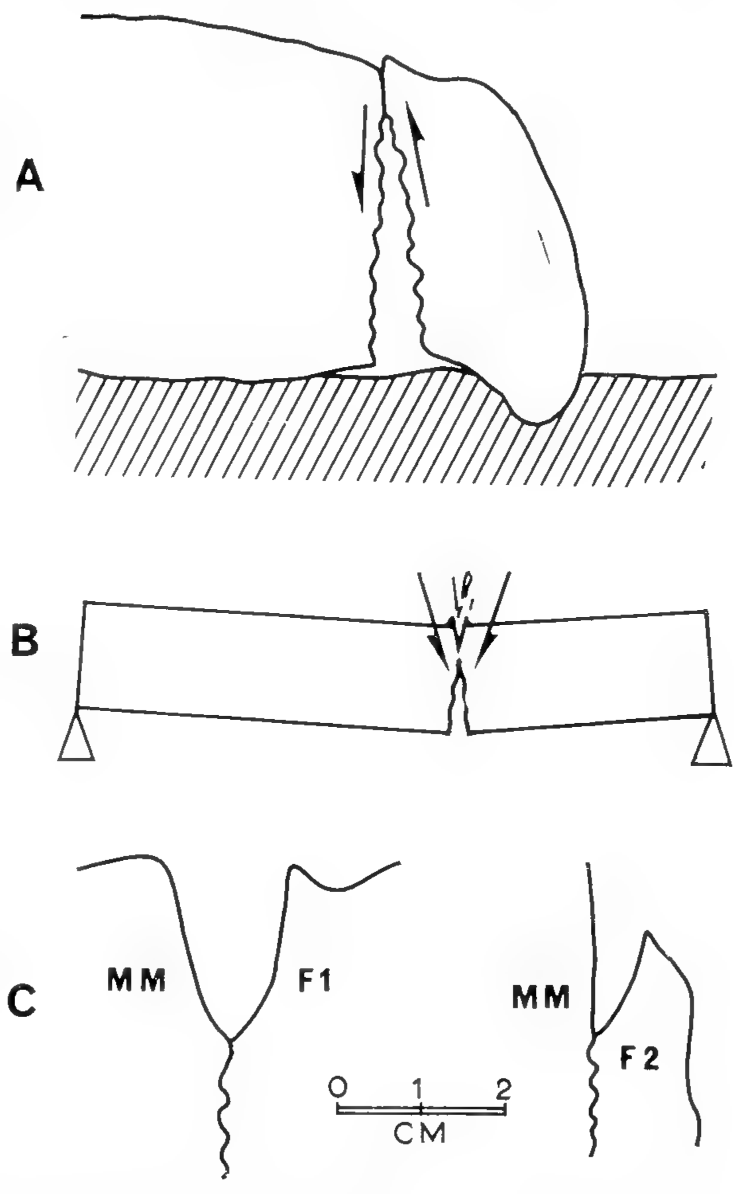

Figure 9. A.—Profile of portion of apical end of Haig meteorite with fragment 1 in course of detachment in a brittle manner. B.—Failure of beam, showing upward development of tension crack and ductile behaviour with ejection of material from the compressed hinge area. C.—Profiles of notches at posterior (hinge) margins of fragments 1 and 2, the main mass in each case on the left.

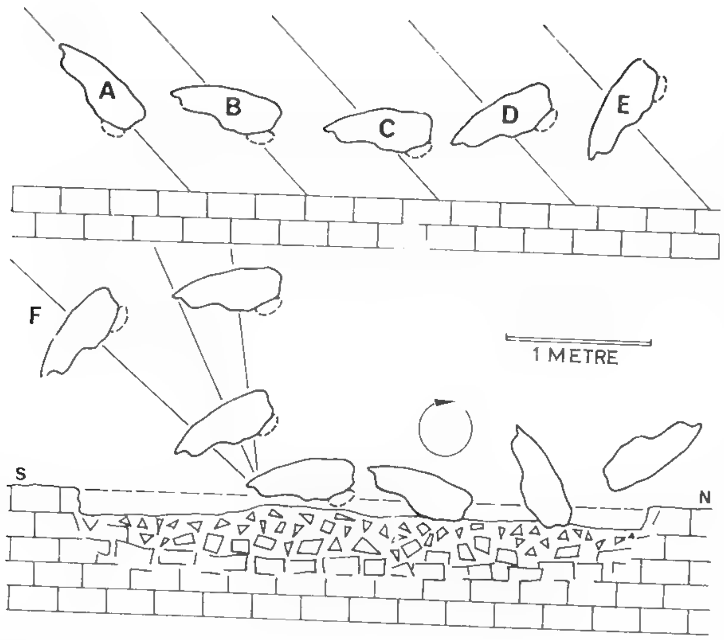

Figure 10.—Profiles of the Haig meteorite seen from the right hand side of flight, the anterior edge of fragment 1 (detached from the side distant to the observor) indicated by the broken line. A. to E.—Orientations relative to the earth's surface with an arbitary angle of trajectory of 45°. F.—Left and top, the limits placed cn angle of trajectory when line of flight coincides with elongation of regmaglypts; below, the favoured orientation and angle of trajectory with diagrammatic sequence of events at impact.

would be detached in the correct direction, and the main mass, now presenting an almost streamlined appearance, could plunge forward and deeper whilst continuing to turn over. There is a limit to the heel and toe action; case E is inadmissible because the extreme heel of the mass was shadowed from damage by the high point nearer to the apex.

Angle of trajectory.—On general principles it appears quite anomalous that a mass of nearly 500 kg should be found 183 m from its site of impact. The attainment of terminal velocity results in the steep angles of trajectory least favourable to ricochet (reported angles are usually 60° or greater, the lower part of the range being more common for the larger masses which are less readily drawn into the vertical by gravity).

The disruption of a mass at low altitude could provide fragments of flat trajectory, but the complete regmaglyptic relief on the Haig meteorite shows that it did not originate in that way.

High angles of trajectory usually lead to one of two results: in unconsolidated ground, a pit is formed, of diameter comparable with the meteorite which is found within it; in harder rocks, especially in the higher range of terminal velocities, a bowl- or funnel-shaped pit many times the diameter of the meteorite is formed by shattering of the meteorite and the ground, and is lined and surrounded by meteorite and rock fragments. Cases of rebound from pits are sufficiently rare to be remarked: two irons of the Sikhote-Alin shower weighing 135 and 300 kg were found 2.5 and 5.5 m from their pits (Krinov 1961, p.86), but the distance here involved is clearly of a different order.

The angle of trajectory can be judged within broad limits by the pattern of debris ejected from the pit. Dr. D. E. Gault (private communication) would infer from this pattern (Fig. 2) an angle of 40° to 50° but adds that the pattern is not inconsistent with angles as low as 20° to 30°.

The alignment of elongate regmaglyps in the line of flight (Krinov 1961, p.251) can be satisfied in a general way by the orientation of Fig. 10D already adopted on other considerations. The angle of trajectory then has a lower limit of 42°—at which angle the heel would be damaged—(Fig. 10F), and an upper limit of 80° (at which angle the anterior face would meet the ground squarely with little tendency to continued forward movement). The mean of these limits is 61° and the angle judged most likely for effective "heel and toe" action is 60°-70°, a result in agreement with general observation.

The resolution of the apparently anomalous behaviour is thus that reaction with the ground was neither purely ricochet nor rebound, but a deflected rebound which gave a strong horizontal component of velocity and focussed material low as in impacts at low trajectory.

Impact pit.—The pit does not fit into any well established category but an explanation can be offered for the distribution of the meteoritic material and limestone fragments. It is suggested that the pit resulted from a shock wave, perhaps with the decompression more or less simultaneous with the meteorite leaving the pit.

The work accomplished in damage to the meteorite, shattering of ground, and continued travel of fragments, is so great that it is of interest to contrast the case of the recently discovered Mundrabilla irons 120 miles to the east-north-east upon the same limestone, and for which no evidence of cratering or bouncing was found (Wilson & Cooney 1967). Except in scale, there are close analogies between the materials; the smaller Mundrabilla iron is a fragment of a larger one found 200 yd distant; they were accompanied by numerous fragments scattered over a wide area (compare main mass, fragment 1 and smaller fragments of Haig). The large Mundrabilla mass (op. cit. Fig. 1) and the main mass of Haig (McCall & de Laeter 1965, Pl. VI A) have the same bluntly wedged shape, and as figured with their fracture scars towards the observer, are nearly mirror images.

It is cautiously suggested, and with deference to the authors, that an impact pit, possibly shallow and inconspicious, might be sought near the limits of distribution of the smaller fragments.

Summary.—The Haig meteorite approached the earth's surface with a velocity of about 500 m/s and at an angle of about 65°, a large triangular face towards the ground, its apex upward and forward in the line of flight. First contact was made with the ground near the broad base of the anterior face, causing the mass to tilt forward until the downwardly propecting left front edge met the ground and was hinged violently outward. Two smaller fragments were similarly detached, and minor fragments were broken

from the anterior edge of the major fracture by octahedral parting of the metal, were plucked from the major fracture, "exploded" from compressed posterior hinges and sheared from prominent points and edges during continued forward movement.

The embedding of the left front edge and the resistance of major fragments to detachment in combination with forward movement resulted in a slight anticlockwise rotation so that continued overturning by "heel and toe" action was deflected to the left of the original path.

The impact shattered thoroughly more than 3 m^3 of limestone, more by shock effect than by direct contact, and about half of it was ejected and focussed low by the forward slumping of the mass; the other half remained within the pit with a record of the impact moulded upon its surface. Insignificant meteoritic material (a few grams with dimensions in millimetres) remained within the pit.

The main mass turned over as it left the pit and probably bounded and rolled during the remaining 183 m of travel, the latter part perhaps irregularly, in the manner of a rolling plate losing velocity.

The axis of the pit and the displaced limestone is directed 10° east of north and is the likely line of flight, but the axis of the sector containing all except a few minor fragments of meteorite is directed due north. The main mass was found only 18 m from the latter axis, a distance not difficult to explain by irregularities of the path, but it was 50 m from the axis of the pit, a distance less readily understandable unless a deflection of 10° occurred during impact.

The largest fragment, with the resultant velocity of forward movement and violent hinging to the right, crossed the flight path of the main mass. Most of the other fragments were scattered within the sector of a circle of angle 35° and radius of 75 metres.

Notes on mineralogy

The mineralogy has been examined only in a slice cut from the heel of the mass (Fig. 5), and thus partially bounded by anterior and posterior faces of the meteorite. Widmanstätten texture is present except in an aerodynamically heated and recrystallized rim adjoining original surface.

Interior.—The approximate true width of kamacite plates, determined by the method of Frost (1965b) is 0.9 mm; the meteorite is therefore a medium octahedrite. Kamacite occurs within the plates as polyhedral grains up to 2 mm across. Taenite selvages have apparent widths 0—0.3 mm, commonly 0.01 mm. The plessite is of both granular and lamellar types. Where seen in relation to each other the boundary of granular plessite, the lamellae of plessite (0.05-0.1 mm wide), and full-scale kamacite bars are parallel and show no textural transition.

The percentages by volume of the metallic constituents, estimated with a Leitz integrating stage by traverses on both sides of the slice are:

	%
Kamacite	85.1
Taenite	1.0
Plessite	13.9

Troilite occurs within kamacite as nodules not commonly exceedng 0.2 mm diameter, in veinlets, and in association with an unidentified mineral; its distribution was confirmed by sulphur prints. Two large nodules lost from the major fracture surface (the larger 1.8 cm diameter), and those represented by small pits on original surface may also have been troilite.

An unidentified mineral is present as a single, dark, hard, lath-shaped crystal measuring 3.0 x 0.4 millimetres. It is enclosed within two adjoining grains of kamacite and contains a few small inclusions, probably of metal. Troilite nodules are present at its ends and sporadically along its edges. The writer was unable to identify this mineral and the additional observations made by Dr. George Baker were also inconclusive. A spectrochemical analysis made by Mr. T. H. Donnelly showed strong lines of silicon. An electron probe microanalysis is to be made.

Thermally altered rim.—The minutely granular heat-affected rim along the edge with greater regmaglyptic relief varies in width from 0.6 mm in hollows to 2.35 mm at an upstanding regmaglypt boundary; along the edge with lower relief the width varies from 1.6 mm in hollows to 3.7 mm on a convex curve. The rim is thus distinctly wider on the posterior than on the anterior edge. Weathering has not affected either face severely in this part of the meteorite. Such greater widths on the posterior face are not unusual when metal ablated from an anterior surface has been redeposited on the posterior (Lovering and others 1960), but no ablation deposit is present in this case. Indeed, relic texture is recognisable throughout the rim because of the persistance of taenite (including that taenite which has a characteristic texture as a component of plessite) after the complete recrystallization of the kamacite.

Comparison with Duketon.—The nickel contents of the Haig meteorite (McCall & de Laeter 1965, p. 35) and of the Duketon medium octahedrite (Frost 1965 a) are similar and the kamacite widths are 0.9 and 1.0 mm respectively. The comparison is made because these are the only two of 30 Western Australian irons which have a complete and well developed cover of regmaglypts. The subdued pattern on the reverse side of Duketon (Frost 1958, Pl. I) is very similar to that on the posterior face of Haig, but the extent to which weathering has contributed to this similarity is unknown; in both cases such relief may be in part a primary feature (compare the Cabin Creek iron—Mason 1962, Fig. 21). The Duketon iron was found 340 miles distant from Haig, but dispersal over comparable or even greater distances has been proposed for groups of hexahedrite irons (Mason op. cit. p. 133), in which the relative rarity of the type is an argument favouring a common origin of the individuals. The argument is not valid in this case but the possibility of relationship is worthy of investigation.

THE MOUNT EGERTON METEORITE

Introduction

The Mount Egerton meteorite was discovered in 1941, but the few fragments received into official collections were apparently lost until investigations made in recent years led to their partial relocation (McCall 1965). The precise site of find remained unknown and the only remaining link with the original discovery was the aged aborigine, Sandy Gaffney.

Mr. A. E. Bain, manager of Mount Clere pastoral station, twice brought Gaffney to the station to indicate the general area of find and to make searches. The site was rediscovered by M. K. Quartermaine and A. E. Bain in 1966, and more than 3000 fragments of aggregate weight 19.0 kg were collected. Dr. Brian Mason and Dr. E. P. Henderson later recovered a further 8 kg, principally small metallic fragments located with the aid of a mine detector. At least 0.64 kg had been previously recovered in 1941; a reputed quantity of 3.7 kg included in that recovery (unpublished laboratory report quoted by McCall 1965, p. 248) is surely a typographical error, as the described fragments total 379 g (Anon 1944). The total recovery is therefore at least 27.6 kilograms.

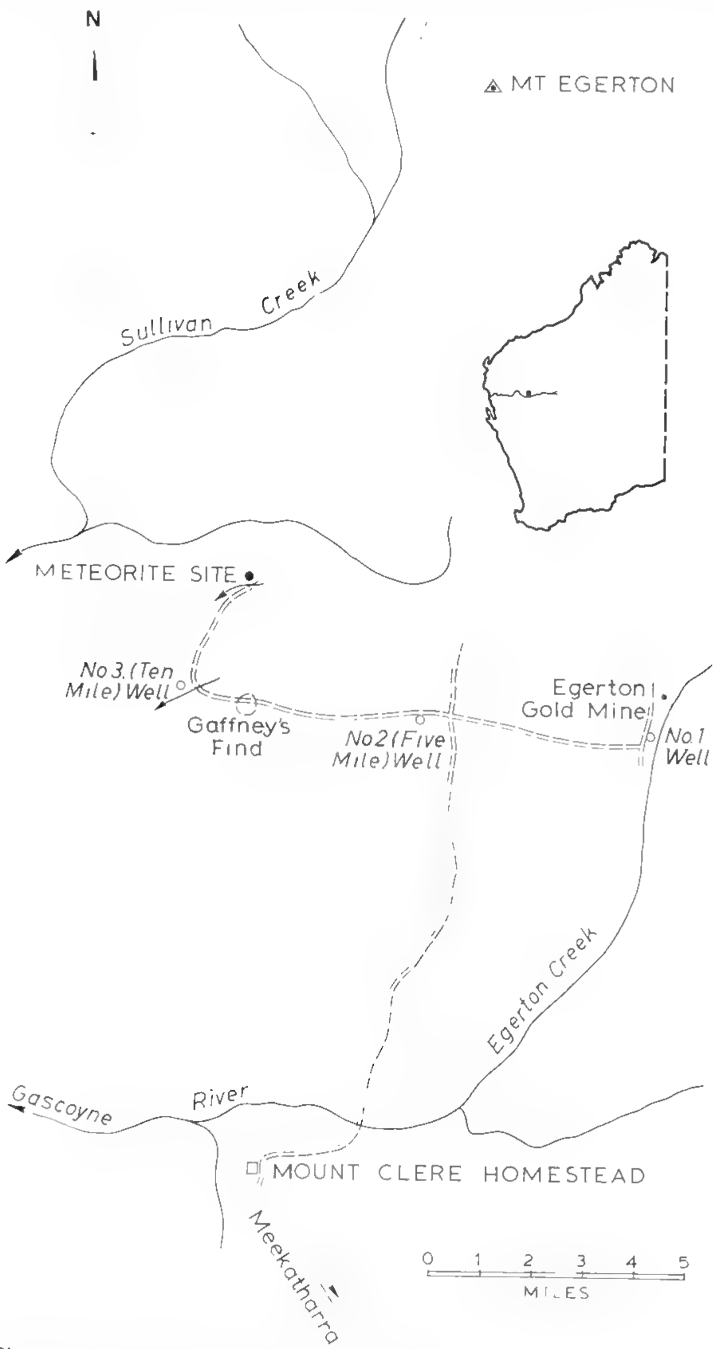

Figure 11.—Sketch map showing site of find of the Mount Egerton meteorite.

The site is 2.4 miles in direction 26° from Mount Egerton No. 3 Well (Fig. 11) and has approximate coordinates 24° 53′S., 117° 38′E.

Field occurrence

Meteorite fragments were abundant near Pit 1 (Fig. 12), the impact pit discovered and excavated in 1941, and near the unexcavated Pit 2. These two concentrations contained more than half of the 19 kg collected by Messrs. Bain and Quartermaine. The 8 kg collected by Dr. Mason and Dr. Henderson came from "around the main hole", in a "fan-shaped area extending 15-20 yd downhill" and "from around the base of a clump of small bushes" (Pit 2), and therefore had the same general distribution. A compact group of five fragments found 18 m from any others represents a third small original mass. The 1941 recovery presumably came from about the excavated pit.

The general direction of flight is inferred to have been easterly, which supports the opinion of Dr. G. J. H. McCall (private communication) that the fireball widely observed to be travelling west-south-west in this district in 1940 was unrelated to the Mount Egerton meteorite first recovered in 1941.

Pit 2 is slightly dished, about 0.6 m in diameter, and in the shelter of a clump of small bushes, a situation much favoured by some ground-dwelling birds. It was free of large stones and overlain by many small and roughly sized pieces of meteoritic enstatite and nickel-iron. The finders regarded it as a bird's nest, but it can be adequately explained as a weather-beaten impact pit. Surface stones would be scattered at the moment of impact, and small pieces of meteorite would remain on the surface as subsequent rain and weather caused the finer material to settle.

The meteoritic material

Textural features.—In bulk, the materal resembles a disintegrated coarse-grained pegmatite, the predominant, well-cleaved enstatite resembling feldspar. Only the occasional coarser-grained metallic segregations attract attention, and it is understandable that only metallic fragments were forwarded to the School of Mines for identification in 1941. The enstatite is of two types, the clear glassy type occurring in vein-like manner within the white type. Fragments illustrate a complete range of proportions of enstatite and metal (Fig. 13), but stony fragments, many of them enstatite cleavage fragments, predominate.

Enstatite grains attain large size. The largest fragment measuring 8.3 x 4 x 3.6 cm, consists of portions of two slightly divergent enstatite grains and some metal (Fig. 13 B); the largest cleavage fragment, measuring 6.7 x 3.4 x 2 cm and weighing 58.9 g, is a rough 45° isosceles triangle in cross section; the original grain could therefore have had at least twice the cross sectional area and weight.

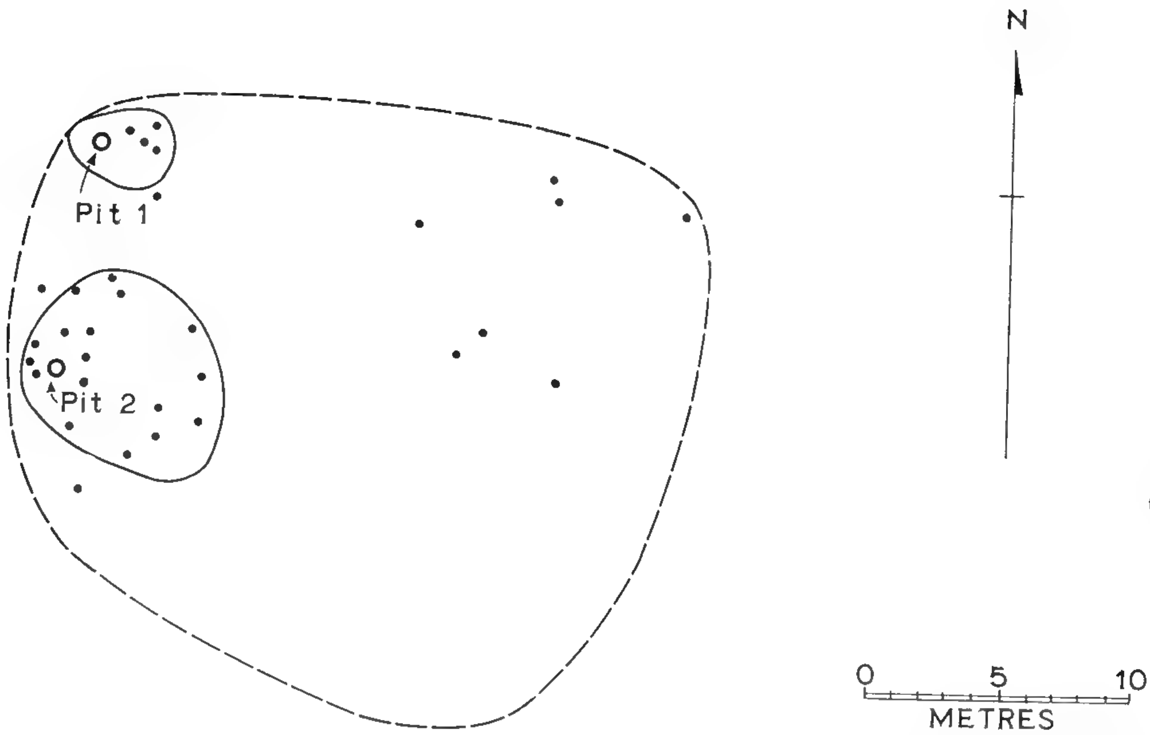

Figure 12.—Field distribution of the Mount Egerton meteorite fragments. Areas containing more than 100g/m^2 enclosed by firm lines; the remaining fragments were within the broken lines. Fragments weighing more than 40 grams indicated by dots (a further five such fragments from the 1941 recovery were probably from the vicinity of Pit 1).

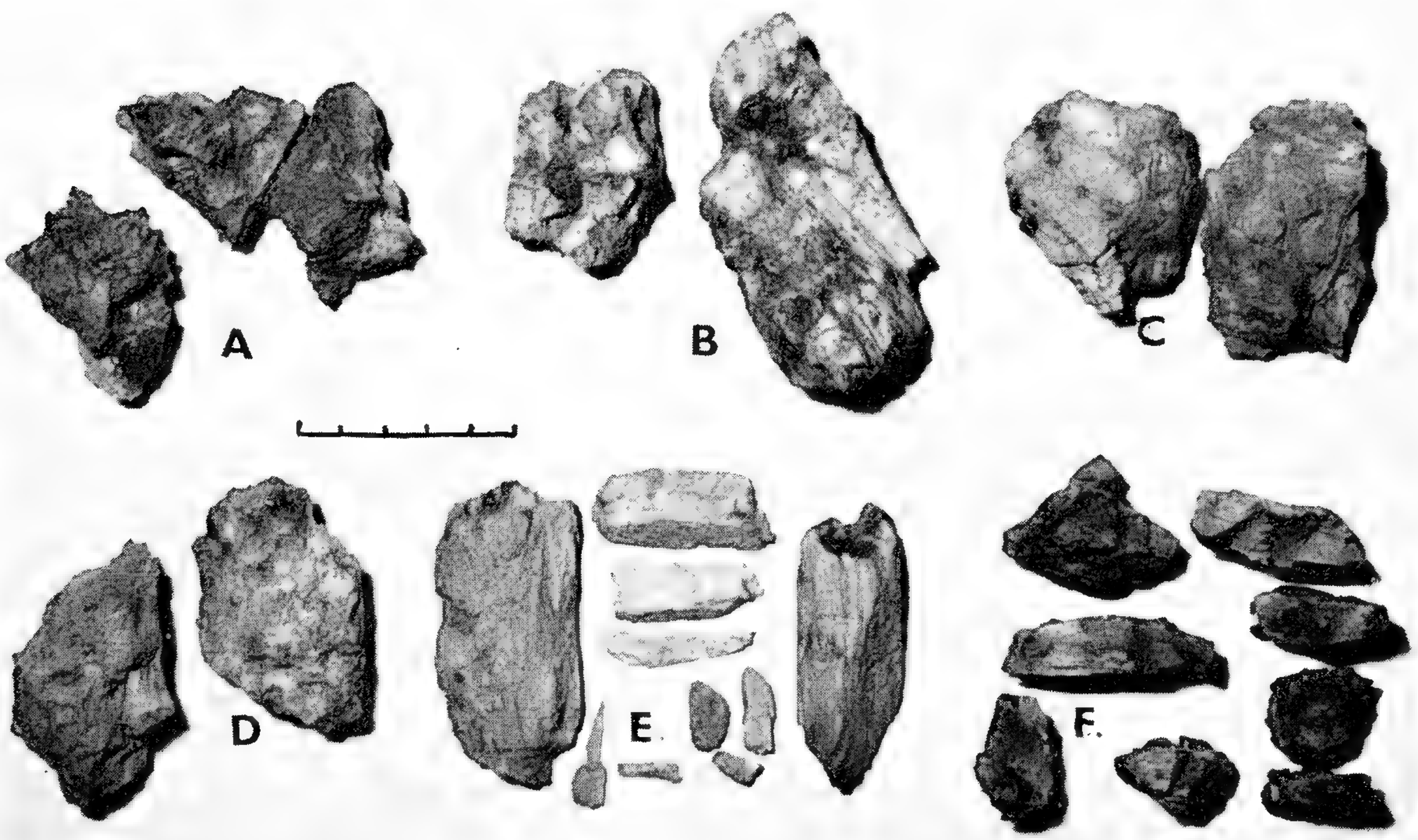

Figure 13.—Types of impact fragments of the Mount Egerton meteorite. A.—Nickel-iron with some adhering and enclosed enstatite; two fitting fragments at right shown slightly separated. B.—Enstatite with coarse grains of metal. C.—Enstatite with finer grains of metal. D.—Type without macroscopic metal. E.—Enstatite cleavage fragments, one showing melt skin over regmaglypt at its upper end. F.—Fragments showing areas of dark melt skin over regmaglypts. Scale in centimetres.

Two fitting fragments (Fig. 13 A) contain metal estimated to weigh 160 g, and two fragments from the original recovery weighing 121.7 g and 83.9 g were described as mainly metallic (McCall and de Laeter 1965). From such large interstitial masses there is a continuous range of size down to grains seen only microscopically within the enstatite.

Textural relationship between enstatite grains can be seen in few fragments. The relationship varies from slightly divergent to completely right-angled with partial penetration. The texture was probably igneous-looking or with elongate enstatite grains in random orientation as in a hornfels.

Fragmentation.—Though the known weight of meteorite exceeds 27,000 g, only 22 fragments are of greater than 50 grams. The lower limit of size has been the purely practical one of field observation and collection. Microscopic grains of enstatite are present in adhering soil, and minute rusty grains of metal are readily collected with a magnet.

The unusually thorough fragmentation can be ascribed to the coarse grain and ready cleavability of the enstatite coupled with the rocky nature of the site.

A prior history of mechanical deformation also provided surfaces along which fracture occurred. Many fragments have areas of hummocky or smoothly dished surface, the latter somewhat resembling regmaglypts but having higher relief. These forms arise from breakage along the contact of the two principal textural types of enstatite. "Veins" of the glassy form may pinch and swell providing either a hummocky surface or its negative equivalent. Microscopically, the clear enstatite show various degrees of strain by multiple twinning, strain shadows, cracking and dislocation. The other type is minutely granulated and neither extinguishes cleanly nor shows the aggregate effect resulting from randomly oriented grains. Instead, strain shadows move across numerous grains in optical continuity, and in parallel bands may move in opposite directions. The material appears to be multiple twinned and shattered by some process which permitted very little rotation of individual grains. There are other textural variants and a variety of boundary relationships. These textures may be the result of a severe shock wave with complex internal reflections.

Original surface features.—Patches of melt skin of up to 4 cm^2 are present on nearly 200 fragments. Occasionally, it is present on two or three sides, suggesting that the fragment was an upstanding part of an irregular surface; in no case is the coverage of skin sufficiently extensive to suggest individuality in atmospheric flight.

The skin commonly overlies regmaglyptic surface, usually portion of a single regmaglypt, rarely three to five. Most regmaglypts are 1 cm or less across with smooth bounding ridges, but a complete oval example measures 2.0 x 1.1 cm and an incomplete one is 2.3 x 2.0 x 0.7 cm deep.

Melt skin is dark grey and opaque, but merging in places into small areas which are brown or light brown and then becoming translucent or transparent. In two cases, a grain beneath the surface of brown skin has a grey opaque halo, suggesting that the pale transparent skin is that normal to the almost iron-free enstatite, and that the much more general, dark, opaque skin shows the influence of the iron-bearing constituents.

The textures of the melt skin are conveniently described in the nomenclature of Krinov (1961, pp. 265-270 and Plates 1-7). The close-textured skin is the most abundant, but the striated texture (including striae with hooked ends, terminal droplets, and crossing striae) and the scoriaceous texture (including examples showing its abrupt termination at regmaglypt boundaries) are also common; knobby, ribbed and porous textures occur rarely. There is thus one common type from each of Krinov's frontal, lateral and rear surface groups.

The close-textured melt skin has a thickness of 0.05-0.11 mm and may show two layers. The inner layer of uniform width is minutely fibrous and orientated more or less normal to the meteorite surface. It appears to represent the first stages of melting extending down the structure of the enstatite. The outer layer, of variable thickness, is glass showing incipient devitrification.

The scoriaceous skin has a thickness up to 0.25 mm and may show three layers, the inner two as for the close-textured skin and the outermost scoriaceous and opaque except where thinned by the presence of bubble cavities where it shows a hematite red by transmitted light. In a typical section, the fibrous layer is 0.03 mm thick, the structureless layer 0.06 mm and the scoriaceous 0.12 mm thick. Because of the similarity of the inner layers to those of the close-textured skin, including the irregular thickness of the second layer, it appears that the scoriaceous layer has flowed over an existing close-textured skin. Volatiles from troilite and schreibersite during their incorporation in the melt may account for the mobility of the material and for its vesiculation.

Short irregular cracks which are sub-parallel to the meteorite surfaces are developed sporadically in a zone about 2 mm thick immediately beneath the melt skin, and are regarded as an exfoliation effect in advance of melting.

Specific gravity.—The specific gravity of the meteorite is important as providing a means of assessing the proportions of the two major constituents; subsequent detailed work can then be integrated into a general analysis or a mode. Because of the extreme variability of the fragments both in size and mineralogical proportions, the whole of the available material was bulked, thoroughly mixed by rolling, coned and quartered several times to provide samples of rather more than 1 kg each. The specific gravities of one sample from each of the final splittings were determined by using a large flask fitted as a pycnometer. The results were in the range 3.50-3.79 with a weighted mean of 3.64. That the range of values represented a true

variation related to the difficulties of sampling such a mixture of sizes and types was demonstrated by reproducibility of results.

Metal content.—The specific gravities of a number of metallic fragments of weights 3-13 g and free of adhering silicate were in the range 7.05-7.66. The variation is greater than can be accounted for by included schreibersite and troilite or by a slightly rusted surface. Included silicate is indicated (McCall 1965, Fig. 6), and the highest reproducible value was therefore accepted. The specific gravity of pure Mg Si O_3 (to which the Mount Egerton material approximates very closely) is 3.20 ± 0.01.

Using the specific gravity values 3.64, 7.66 and 3.20 for meteorite, metal and enstatite, the metal content of the meteorite is calculated to be 21.0% by weight and 9.9% by volume, or for practical purposes, one fifth and one tenth respectively.

Size of masses.—From the weight and specific gravity of the meteorite, the fragments are calculated to be equivalent to a spherical mass nearly 30 cm in diameter, or to two masses of about 17 cm and 27 cm diameter (apportioned according to the weights of material closely associated with Pits 1 and 2 respectively).

Discussion

The Mount Egerton meteorite closely resembles Shallowater, which is usually classed with the enstatite achondrites, though containing 12% of metal plus troilite (Mount Egerton 21%). Both have features common to, and intermediate between those of the enstatite chondrites and the enstatite achondrites which have been claimed to have been derived from them (Lovering 1962; Ringwood 1962; Morgan and Lovering 1964). A comparison is made in Table 1 drawing principally upon the work of Foshag (1940), McCall (1965) and Mason (1966).

The essential mineralogy is a nearly iron-free form of Mg Si O_3, and metal containing about 6% nickel (often showing evidence of strong reduction in the presence of silicon or perryite), the amount of metal and troilite declining to the achondrite end. Texturally, Mount Egerton and Shallowater resemble the achondrites in their coarseness of grain, and the chondrites in their lack of brecciation.

There is also similarity between the metal phase of Mount Egerton and the small (0.57 kg) Horse Creek iron (McCall 1965, p.243), both of which contain perryite. Dr. E. P. Henderson (private communication) suggests that Horse Creek may be a metallic mass from a meteorite of the Mount Egerton type, of which the silicate phase was not recovered.

The new recoveries will make possible detailed studies of the Mount Egerton meteorite, but tentatively it is conveniently grouped with Shallowater as an unusually metal-rich, unbrecciated, enstatite achondrite.

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Messrs. A. J. Carlisle, A. E. Bain and M. K. Quartermaine found and donated the Haig and Mount Egerton material to official collections. Mr. Quartermaine also kept careful field records at both sites. The main mass of the Haig meteorite was made available by the Director of the Western Australian Museum, Dr. W. D. L. Ride, whose staff, and especially Mr. Duncan Merrilees, were most helpful.

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TABLE 1

Textures and mineralogy of enstatite-rich meteorites

	Enstatite chondrites (15)	Mount Egerton	Shallowater	Enstatite achondrites (8)
Texture and Structure	Chondritic to finely granular (when recrystallized) with small metal grains evenly distributed	Extremely coarse-grained enstatite with coarse to fine interstitial metal and some included fine grains	Very coarse-grained enstatite with small grains of included and interstitial metal	Coarse-grained enstatite, accessory metal
	Usually unbrecciated	Incipient brecciation (Shock induced?)	Unbrecciated	Thoroughly brecciated
Dominant silicate	Almost iron-free clino-enstatite (in chondritic type) and/or enstatite (in recrystallized type)	Almost iron-free enstatite	Almost iron-free enstatite	Almost iron-free enstatite Occasional accessory-clino-enstatite
Accessory silicates	A silica mineral in chondritic members, oligoclase in recrystallized ones	None recorded	Oligoclase 2 % Olivine 5 %	Oligoclase and Olivine sometimes present
Nickel-iron. Weight%	19 to 28 %	21 % (including troilite and other accessories)	9 %	Accessory
Triolite. Weight %	7 to 15 %		3 % (includes other accessories)	Accessory
Nickel content of metal	c. 6 %	6.38 %	6.83 %	c. 6 %
Schreibersite ...	Often accessory	Present	Vivianite (weathering of schreibersite?)	Known in accessory amount

of C.S.I.R.O. Mineragraphic Investigations, Melbourne, Dr. M. J. Frost of the British Museum, and Messrs. R. J. Hardy and A. J. Blackwell of the School of Mines of Western Australia. For the use of a vehicle and School of Mines facilities, thanks are due to the Director, Mr. R. A. Hobson.

Dr. Brian Mason kindly read the manuscript and offered constructive criticism on a number of points.

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9.—Some petrological features of a spinel-bearing metagabbro in the pyroxene granulites of the Fraser Range, Western Australia

by Allan F. Wilson & D. D. Middleton*

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Abstract

A preliminary study of a body of spinel-bearing metagabbro, 73½ miles east of Norseman, shows obvious textural, mineralogical and chemical differences between the fine-grained marginal facies and the coarse-grained central facies of the body. These differences may be of primary igneous origin or they may represent a response to later granulite facies metamorphism. Tectonic granulation possibly accounts for the absence of olivine in the marginal facies.

Variation of 2V within individual augite grains and the presence of haloes of andesine around spinel inclusions in labradorite suggest solid-state diffusion. Patchy concentration of volatile components appears to have controlled similar patchy development of clots of amphibole and carbonate. The presence of a titanium-rich amphibole (kaersutite) is a prominent mineralogical feature of the rocks.

Introduction

Several small low hills of well exposed metagabbros near the Eyre Highway 72 to 73 miles east of Norseman were mapped between the years 1952 and 1960. A description of the metamorphic phenomena exhibited by the spinel-bearing metagabbro is one of several projects which have been centred on a region known as the Allanite Pegmatite locality, 73½ miles from Norseman. A map of this region has been published in the paper recording the analytical data from the allanite pegmatite (Wilson, 1966) and here appears in modified form as Figure 1 of this paper.

The region is composed dominantly of basic pyroxene granulites, and metagabbro dykes. Many of the granulites are metavolcanic rocks. The allanite pegmatites which cut the granulites have not been metamorphosed. The "ages" of the pegmatites determined by K/Ar and Rb/Sr on Muscovite are 1210 x 10^6 years and 1280 x 10^6 years respectively. (Wilson, *et al.*, 1960, Table 1, No. 22). The true age is likely to be close to 1280 x 10^6 years.

Structure

The map shows two outcrops of metagabbro which have similar petrological features. The largest outcrop has been selected for detailed study. A specimen from this locality (Spec. 24522W) was briefly described in a reconnaissance study of parts of southern Western Australia. (Clarke, *et al.*, 1954, p. 40).

The metagabbro is now a lenticular body set in pyroxene granulites. The gabbro has been recrystallized more at the edges of the body than in the coarser central portions, so much so that it is not easy to delineate the original gabbro-granulite contact. The finer grained border facies of the gabbro has been converted to a pyroxene granulite. One of the purposes of the mineralogical study of one of these border granulites (Spec. 16307) is to see if there are distinctive features of the minerals which may aid in deciphering the several phases of igneous activity and metamorphism which have affected the region.

Structurally, the most obvious difference between the granulites intruded by the gabbro and the granulites formed by recrystallization of the margins of the gabbro is that the former show well developed tight shear folds and megascopically lineated pyroxenes, quartz and feldspar particles. The granulites formed from the gabbro, however, show no megascopic lineation, and are much more homogeneous than are the granulites thought to be derived from the basic volcanic rocks. In this locality the foliation of the granulites appears to be parallel to the primary structures of the metamorphosed volcanic rocks.

The lineation and fold-axes of the country rocks are coincident, and the map shows that the general structural trend is that of the whole Fraser Range (which extends about 14 miles westward to the Fraser "Fault"—Wilson, 1965). Plunges of minor fold-axes are steep in this region but are commonly shallow in the more rigidly aligned granulites further to the west.

Although the granulites formed from recrystallization of the gabbro show no obvious megascopic lineation it is likely that some deformation accompanied their metamorphism which was essentially a thermal metamorphism.

Petrography

Although petrographic study reveals a large variation in mineral proportions and grain size in the metagabbro, most of the boundaries are not obvious in the field. The metagabbro is mostly olivine-bearing, and ranges in composition from a meta-eucritic norite to a metanorite. Rhythmic banding is generally absent. However, a large irregular block of metagabbro was observed (Spec. 41856W) which has crude banding, with strike 15°, dip 65°E. Banding and grain size of this and related rocks is so coarse that it could scarcely have been developed within the present boundaries of such a narrow gabbroic body. This suggests that the metagabbro is a relic of a much larger, possibly, flat-lying body which has become broken up during a late phase of granulite metamorphism.

In this paper only the more normal rock types are described. These are illustrated by a series of specimens collected from the centre of the lenticular body (Spec. 16311) to its western contact (Spec. 16307) (see Fig. 1).

* Department of Geology and Mineralogy, University of Queensland

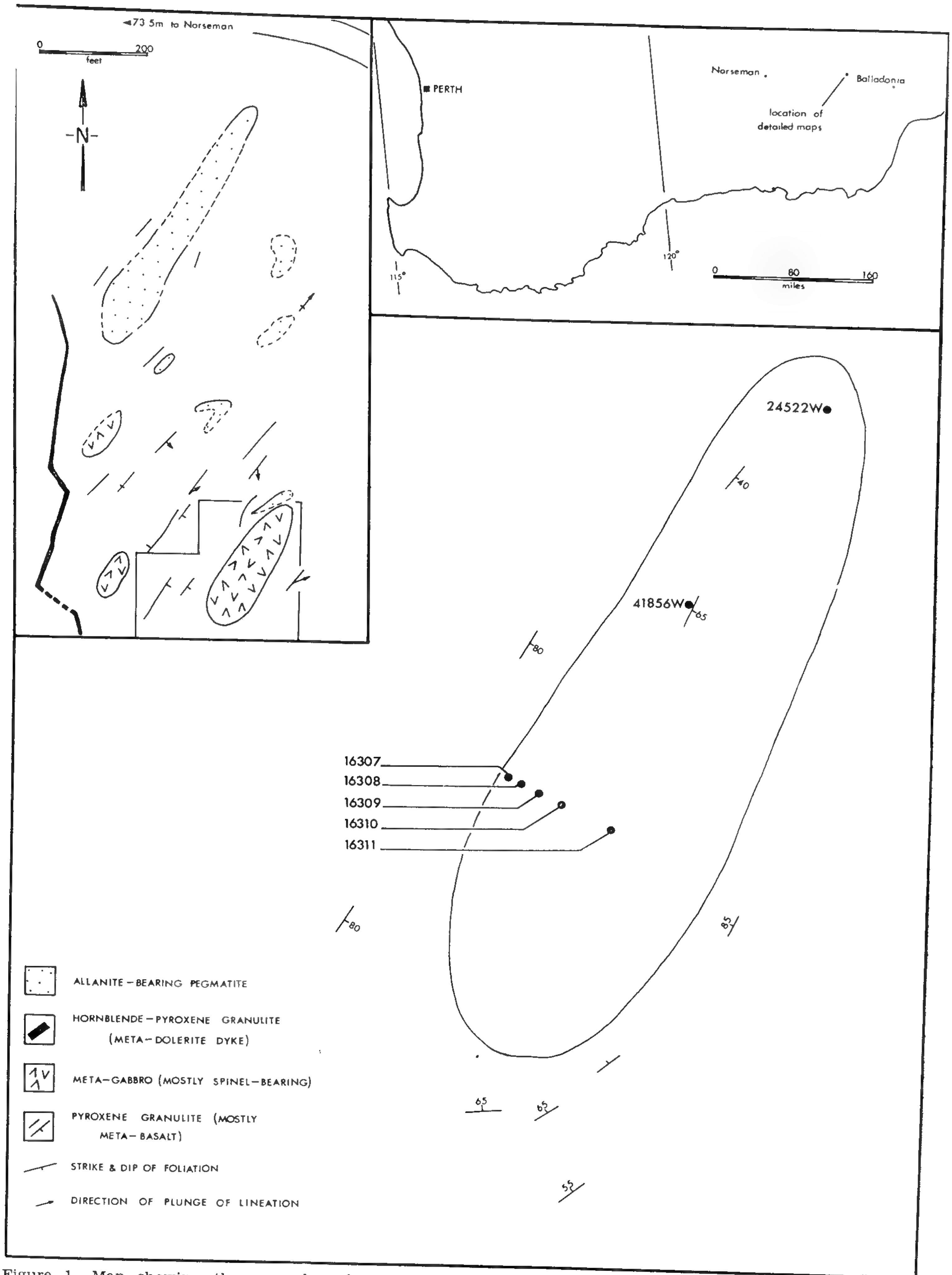

Figure 1.—Map showing the general geology and location of the spinel-bearing metagabbro body. The map on the lower right shows the position of specimens referred to in the text.

Coarse-grained spinel-bearing rocks

Spinel occurs principally in the coarse-grained central portion of the body, of which Spec. 16311 and 24522W are characteristic. Although partially recrystallized, the original gabbroic, subophitic texture with plagioclase partially enclosed by pyroxenes is still recognisable. Concentrations of mafic minerals are common.

Plagioclase (An_{52}) occurs as subhedral and anhedral grains, often elongate, up to 4 mm in length. A few grains, show normal zoning from An_{67} to An_{52}. Most grains show well developed albite twinning. However, although there is no evidence of deformation the twin lamellae of some grains are irregular or discontinuous. Most grains contain abundant inclusions of euhedral green spinel whose development has impoverished the adjacent host plagioclase in anorthite content. Thus the spinel grains are enclosed by haloes of andesine which vary in composition from An_{37} to An_{42}. (See Fig. 2.)

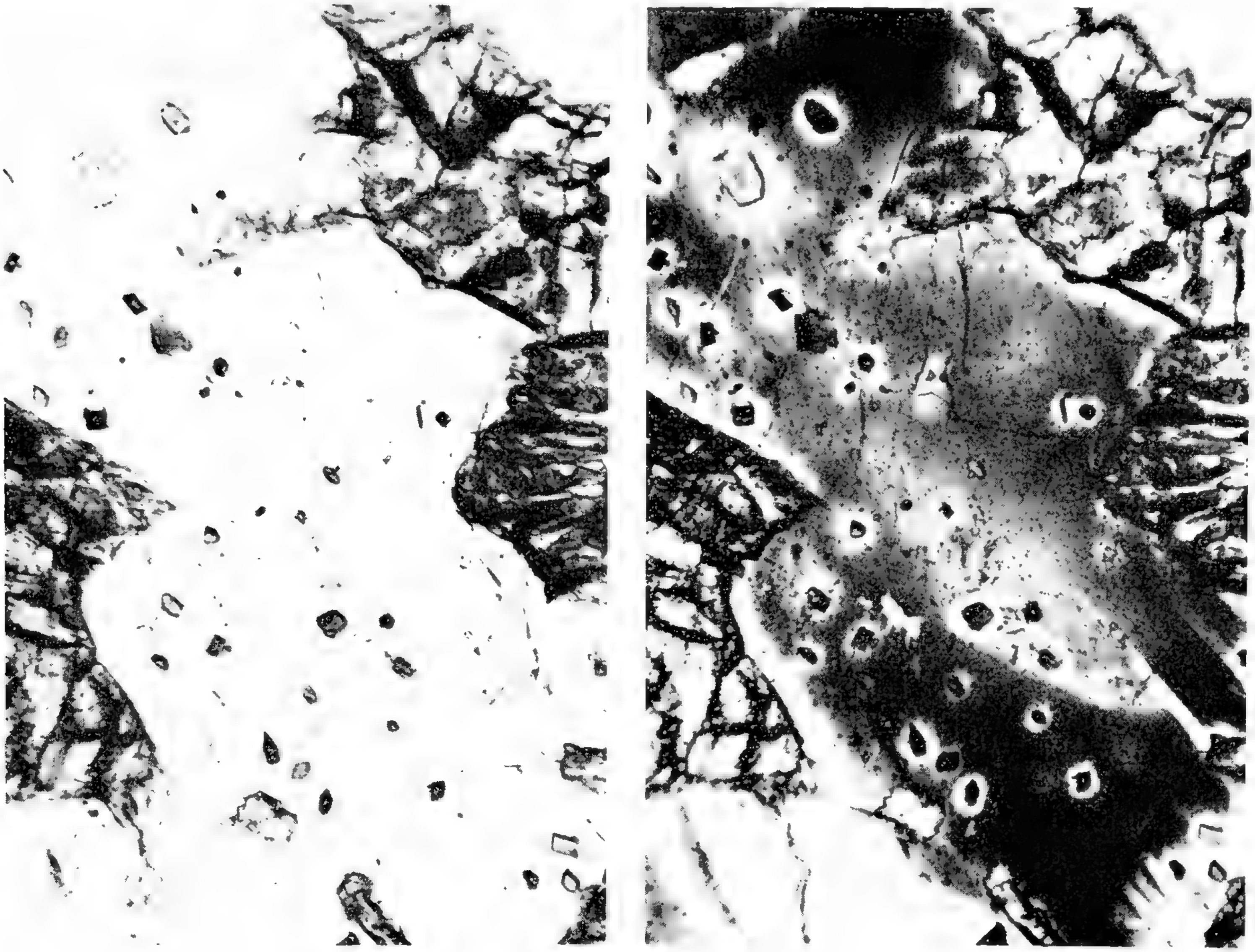

Figure 2.—A (left) Photomicrograph of a plagioclase grain (white) in Spec. 16311 showing euhedral spinel inclusions (shades of dark grey). The other dark mineral is clinopyroxene which contains some vermiform spinel inclusions. Plain light, X80. B (right).—Same field of view as Figure 2A with nicols crossed. Note the andesine haloes around spinel inclusions in the labradorite host.

Hypersthene occurs in two forms: (i) as anhedral grains (0.5 mm to 3.0 mm) which contain inclusions of spinel and olivine. Exsolution lamellae up to 0.04 mm in width are common. (ii) as small anhedral grains (up to 0.5 mm) which are devoid of exsolution lamellae. They form part of a granular aggregate of hypersthene, augite, spinel and olivine. Both forms are very faintly pleochroic and no compositional differences are apparent. In Spec. 16311, $\alpha = 1.713$, $2V/\gamma = 63^\circ$; composition using γ is Fs37 (Deer, Howie & Zussman, 1962, 2: 28).

Augite occurs as anhedral grains (up to 4 mm) which commonly show patchy or undulose extinction. Exsolution lamellae are common. The augite, hypersthene, spinel and olivine commonly form granular aggregates which appear to pseudomorph an original gabbroic texture. A notable optical property of the augite is that variation in 2V demonstrates marked variation in composition within some augite grains. Figure 3 illustrates this phenomenon. In Spec. 16311, the normal value for $2V\gamma$ is 49° whereas it is about 57° near plagioclase and about 42° near olivine. $\beta = 1.700$. The composition approximates $Ca_{40}Mg_{36}Fe_{24}$ (Deer, Howie & Zussman, 1962, p. 132).

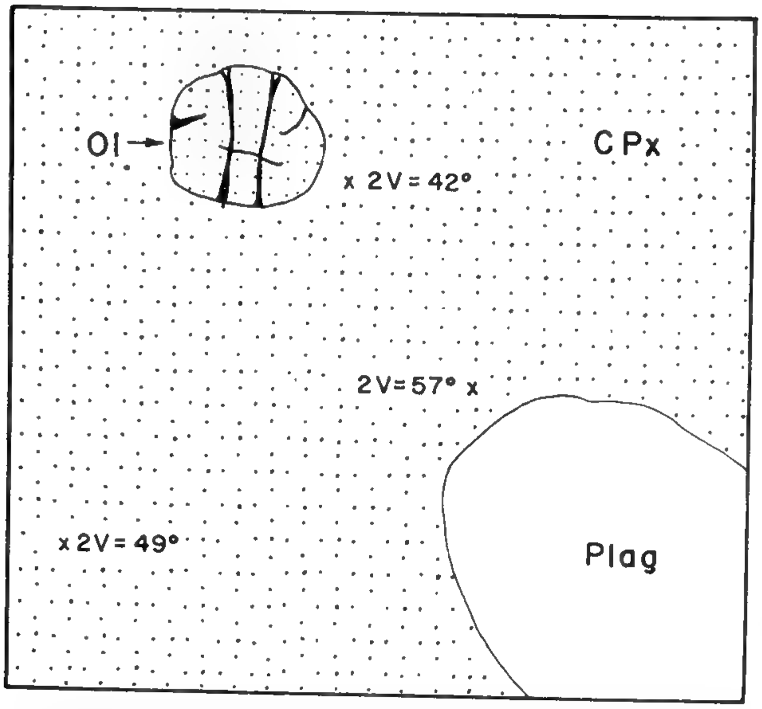

Figure 3.—Sketch illustrating solid-state diffusion in the coarse-grained facies of the metagabbro as shown by variation in 2V/∿ measured within a single grain (CPx) in Spec. 16311. Near plagioclase (white), 2V=57°, whereas near the olivine grain (Ol) 2V=42°. The normal 2V is 49°. Approx. X50.

Amphibole. The presence of a strongly pleochroic titaniferous amphibole (a kaersutite—see Table 1 for analysis and optical data of kaersutite from 24522W) is one of the most prominent mineralogical features of the metagabbro. The pleochroism is X = pale yellow, Y = medium red-brown, Z = deep red-brown. The kaersutite forms aggregates of anhedral grains (up to 1.5 mm) which are commonly dispersed between the somewhat more fine-grained pyroxene-spinel-olivine aggregates.

Olivine (chrysolite—see analysis and optical data, Table 2) occurs as small anhedral grains (up to 0.5 mm) which may be included in the mafic minerals of the granular aggregates and in some of the larger plates of augite.

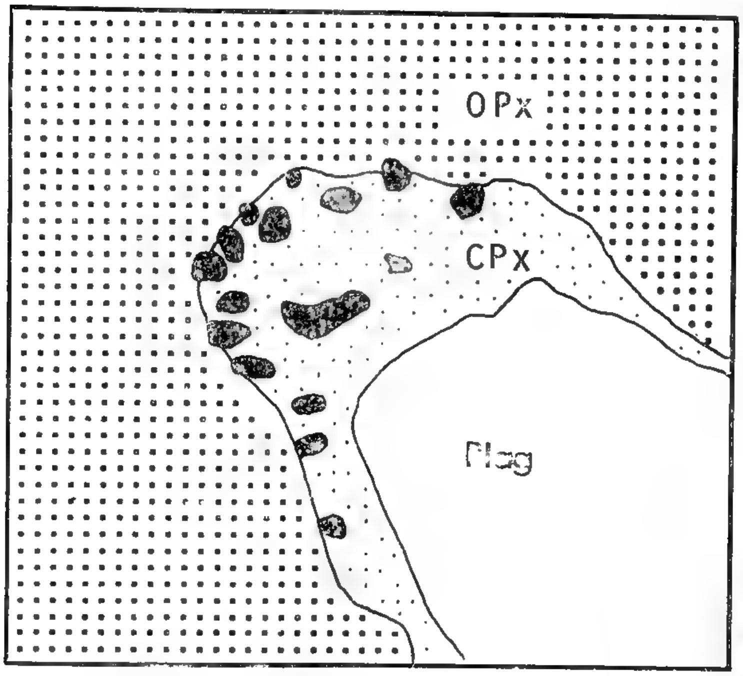

Figure 4.—Sketch showing a reaction texture in Spec. 16311. A granular aggregate of spinel (black) and augite (light stipple, CPx) is shown separating hypersthene (coarse stipple, OPx) and plagioclase (white). Approx. X50.

Spinel (pleonaste) occurs in two forms: (i) as stout euhedral crystals in plagioclase. The crystals commonly range in size from 0.02 mm to 0.04 mm (up to 0.1 mm), and are fairly evenly distributed throughout the host. However, in some instances there is a concentration of spinel crystals along some of the twin planes of the plagioclase.

(ii) As anhedral grains scattered throughout all of the mafic minerals. Spinel is uncommon in the centres of large hypersthene grains. However, it is commonly concentrated at the margins of these grains. In Figure 4 an aggregate of spinel and augite is shown separating hypersthene and plagioclase.n = 1.776 ± 0.003, a= 8.140Å.

The accessory minerals, ilmenite, biotite, apatite and calcite are rare. The biotite is strongly pleochroic in red-browns and is commonly associated with amphibole as also is calcite.

Toward the margin of the metagabbro body the rocks are progressively more strongly re-

Figure 5.—Photomicrograph of Spec. 16307 showing minute rods of almost opaque spinel (black) included in plagioclase (pale grey). The other dark minerals are clincpyroxene (dark grey) and kaersutite (black). Plain light, X100.

crystallized. Although some elongate plagioclase grains occur in Specs. 16310, 16309 and 16308 a gabbroic texture is difficult to recognize. Toward the margin of the body plagioclase is recrystallized to form aggregates of polygonal grains. Spinel and olivine occur in the same manner as in Spec. 16311 but are progressively less plentiful. Olivine has been virtually eliminated in Spec. 16309.

Marginal facies

The marginal portion of the body is represented by Spec. 16307. This has been completely recrystallized to an aggregate of polygonal grains normally ranging in size from 0.5 mm to 1 mm.

Plagioclase forms well twinned grains (0.5 mm to 0.8 mm), and shows slight normal zoning which varies from An_{50} to An_{55}. The plagioclase contains only tiny spinel inclusions in contrast with that of the coarser rock, Spec. 16311. They occur as minute rods which are an average length of about 0.003 mm (Fig. 5).

Hypersthene occurs as anhedral grains and aggregates of grains up to 3 mm, averaging 0.5 mm. Fine exsolution lamellae are common. It is moderately pleochroic with X=pale pink, Y=pale yellow, Z=greenish-grey.

Amphibole, a strongly pleochroic titaniferous amphibole, is a prominent feature of both this rock and the coarse-grained rocks.

Augite is much more granular than in the coarse metagabbro, and is normally associated with granular hypersthene in aggregates. A chemical analysis shows it to be a calcic augite, $Ca_{44.4}$, $Mg_{37.2}$, $Fe_{18.4}$ (Table 3).

Mineralogy

Amphibole

The amphibole from Spec. 16307 and 24522W differs somewhat from the more normal brown hornblende of granulite facies rocks. Prider, (Clarke, *et al.*, 1954, p. 40) in describing the amphibole from Spec. 24522 noted its unusual pleochroic colours which are reminiscent of barkevikite. He pointed out that this is the only occurrence of this deep reddish-brown amphibole in the collection of Precambrian rocks from southern Western Australia.

TABLE 1

Amphibole analyses

	1	2	3	4	5	6	7
SiO_2	38.83	38.94	40.65	39.20	39.83	40.88	42.17
TiO_2	4.71	5.38	4.52	4.88	2.56	0.22	2.39
Al_2O_3	14.29	15.30	17.12	13.25	14.98	11.04	12.22
Fe_2O_3	3.66	2.02	4.26	2.97	7.66	7.56	3.28
FeO	10.43	9.98	5.53	10.49	3.78	17.41	14.42
MnO	0.00	0.00	0.34	0.17	..	1.32	0.17
MgO	10.22	10.52	9.96	11.57	14.44	5.92	9.42
CaO	12.22	12.66	12.88	12.59	12.39	10.46	11.46
Na_2O	1.84	1.89	1.74	2.68	2.27	3.75	1.51
K_2O	2.13	1.92	2.80	0.88	1.25	0.78	1.41
P_2O_5	0.07	0.05					0.06
H_2O+	1.57	1.62	0.36	1.17	0.58	1.16	1.50
H_2O-	..	...		0.02			
F	0.21	0.23		0.00	..	.	0.17
	100.18	100.51	100.16	99.87	99.74	100.50	100.18
Less O = F	0.09	0.10	.		..	.	
Total	100.09	100.41	100.16	99.87	99.74	100.50	100.18

Numbers of ions on the basis of 24 (0,OH,F)

	1		2		3		4		5		6		7	
Si	5.823		5.776		6.044		5.908		5.919		6.377		6.383	
P	0.009	8.00	0.006	8.00	....	8.00	...	8.00	...	8.00	..	8.00	...	8.00
Al	2.169		2.218		1.956		2.092		2.081		1.623		1.617	
Al	0.357		0.458		1.044		0.262		0.543		0.407		0.548	
Ti	0.531		0.600		0.506		0.553		0.286		0.025		0.270	
Fe^3	0.413	4.89	0.226	4.85	0.476	4.96	0.336	5.09	0.857	5.35	0.886	5.14	0.371	5.13
Mg	2.284		2.326		2.207		2.598		3.198		1.376		2.114	
Fe^2	1.308		1.238		0.688		1.322		0.470		2.271		1.816	
Mn					0.043		0.022		..		0.174		0.021	
Na	0.535		0.544		0.502		0.782		0.654		1.134		0.439	
Ca	1.963	2.91	2.012	2.92	2.051	3.08	2.033	2.98	1.972	2.86	1.748	3.04	1.850	2.56
K	0.407		0.364		0.530		0.168		0.238		0.156		0.269	
OH	1.571	1.67	1.603	1.71	0.358	0.36	1.177	1.18	0.575	0.58	1.208	1.21	1.506	1.59
F	0.100		0.108		..		.		..		...		0.080	
$\frac{100Mg}{Fe^{+2}+Fe^{+3}+Mg+Mn}$	57.0		61.4		64.6		60.7		70.6		29.2		46.6	
α	1.673		1.675		.		1.681		1.667		1.691		1.670	
γ	1.704		1.705		....		1.700		1.688		1.707		1.692	
$2V/\alpha$	80°(est.)		80°(est.)		..		82°							

1. Kaersutite, Spec. 16307, metagabbro, Fraser Range, Western Australia
2. Kaersutite, Spec. 24522W, metagabbro, Fraser Range, Western Australia
3. Kaersutite, hornblende monchiquite, Deer, Howie & Zussman, 1960, **2** : 322, no. 3
4. Kaersutite, melanocratic comptonite, Deer, Howie & Zussman, 1960, **2** : 322, no. 8
5. Basaltic hornblende, tephrite, Deer, Howie & Zussman, 1960, **2** : 317, no. 3
6. Barkevikite, nepheline syenite, Deer, Howie & Zussman, 1960. **2** : 329, no. 3
7. Average of ten analyses of brown hornblende from granulite facies rocks, Colton, New York. (Engel, *et al.*, 1964, Table 3, p. 138)

The amphibole is strongly pleochroic in shades of red-brown and has higher refractive indices than for common hornblende. The value of 0.5 to 0.6 atoms of Ti per formula unit is more than twice the normal maximum value for Ti in other amphiboles. The replacement of Si by Al of approximately 2 atoms per formula unit is more than twice the normal maximum value for Ti in other amphiboles. The replacement of Si by Al of approximately 2 atoms per formula unit is close to the theoretical limit and is greater than is usual in brown hornblendes of granulite facies rocks (see Table 1). The amphibole from the metagabbro also has higher alkalis than for common hornblende.

These features are characteristic of kaersutitic amphiboles. However, kaersutite cannot always be easily distinguished from barkevikite and basaltic hornblende in thin-section. Table 1 shows analyses of Spec. 16307 and 24522W compared with published kaersutite analyses together with an analysis of a basaltic hornblende and of a barkevikite.

Basaltic hornblende is characterized by a high Fe^{+3}/Fe^{+2} ratio, and low hydroxyl content. The Mg content is invariably higher than the total Fe, and in this respect basaltic hornblende shows marked contrast with kaersutite.

The main differences between barkevikite and kaersutite are the higher content of total Fe in barkevikite, and the high content of Ti in kaersutite. Barkevikite also has a smaller amount of Al, and may contain comparatively high Mn.

Strong similarities in the relative proportions of the major oxides in Spec. 16307 and 24522W and in the published kaersutite analyses are evident.

However, there are slight differences between Spec. 16307 and Spec. 24522W, notably in the proportions of Al in six-fold co-ordination (Al^{vi}), Ti, Fe^{+3}, Fe^{+2} and Mg. The variation may be explained in terms of the substitution relationship:

$$(Al^{vi}, Fe^{+3}, Ti) \longrightarrow (Mg, Fe^{+2})$$

Lower Fe^{+3} and Fe^{+2} in Spec. 24522W compared with Spec 16307 is compensated for by appropriate increase in Al^{vi}, Ti and Mg so that the sum of the atoms of Al^{vi}, Fe^{+3} and Ti and of Fe^{+2} and Mg are comparable for both amphiboles, as indicated below:

	16307	24522W
Al^{vi}	0.357	0.458
Ti	0.531	0.600
Fe^{+3}	0.413	0.226
	1.301	1.284
Mg	2.284	2.326
Fe^{+2}	1.308	1.238
	3.592	3.564

The reason for the variations cannot be readily explained, for the host rocks are similar in bulk composition (see Table 4). However it is evident that the minerals in Spec. 24522W do not represent an equilibrium assemblage, whereas those in Spec. 16307 have closely approached this condition. This fact provides a possible explanation for the variations discussed.

Pyroxenes

The co-existing pyroxenes from the recrystallized margin of the metagabbro (Spec. 16307; see Table 3 for analyses) do not appear to differ appreciably from co-existing pyroxenes of other granulite terranes. The proportions of the major oxides fall well within the known limits of composition of granulite facies pyroxenes. The distribution coefficient with respect to Mg-Fe (K_D—see Table 3) is 0.562 for the coexisting pyroxenes. This falls within the raneg of K_D observed for coexisting pyroxenes of normal granulites.

Due to the problems attendant on preparation and analysis of meaningful samples of exsolved pyroxenes, the pyroxenes from the central portion of the gabbroic body have not yet been analysed.

TABLE 2

Chemical analysis of olivine from metagabbro, Spec. 16311, Fraser Range

	Fraser Range 16311
SiO_2	38.80
TiO_2	
Al_2O_3	0.46
Fe_2O_3	0.75
Cr_2O_3*	0.005
FeO	23.96
MnO	0.32
NiO*	0.065
MgO	35.26
CaO	0.29
Na_2O	tr.
K_2O	tr.
H_2O^+	
H_2O	
	99.91
Ions on basis of 4 oxygens	
Si	1.018
Al	0.014
Ti	....
Fe^{+3}	0.015
Cr	...
Mg	1.378
Ni	0.001
Fe^{+2}	0.526
Mn	0.007
Ca	0.008
γ	1.691
α	1.715
β	1.730
$2V/\alpha$ (est.)	85°

* Determined on optical spectrograph

Olivine

The analysis of the olivine from Spec. 16311 shows that it is an iron-rich chrysolite (Fa 27.6). Recalculation of an analysis of the whole rock (Spec. 16311) shows that the composition of the normative olivine is comparable (Fa 26). However the norm implies the presence of about 37% olivine in Spec. 16311, whereas it contains only about 8% in the mode. This discrepancy is probably due to the presence of amphibole in

TABLE 3

Analysis of co-existing clinopyroxene and orthopyroxene from metagabbro Spec. 16307, Fraser Range.

	1		2	
SiO_2	50.37		51.31	
TiO_2	0.89		<0.01	
Al_2O_3	4.39		1.29	
Fe_2O_3	3.20		1.17	
FeO	7.86		23.90	
MnO	0.05		0.26	
MgO	12.20		20.81	
CaO	20.27		0.74	
Na_2O	0.73		0.12	
K_2O	0.03		0.03	
P_2O_5	<0.01		0.06	
	99.99		99.69	
Ions on basis of 6 oxygens				
Si	1.881		1.942	
P		2.00	0.002	2.00
Al	0.119		0.056	
Al	0.074		0.002	
Ti	0.025		....	
Fe^3	0.090		0.033	
Mg	0.679		1.174	
Fe^2	0.246	1.98	0.757	2.01
Mn	0.002		0.008	
Ca	0.811		0.030	
Na	0.053		0.009	
K	0.001		0.001	
Mg	37.2		58.9	
Fe	18.4		39.6	
Ca	44.4		1.5	
β	1.700		1.713	
2V	+51°		—63°	
Kd*		0.562		

1. Clinopyroxene, Spec. 16307, metagabbro, Fraser Range, W.A.
2. Orthopyroxene, Spec. 16307, metagabbro, Fraser Range, W.A.

$$* \; Kd = \frac{\dfrac{Mg}{Fe^{+2}} \; OPx}{\dfrac{Mg}{Fe^{+2}} \; CPx}$$

the rock which is not taken into account in CIPW normative calculations. Moreover, in the recrystallized rock 16307 (which contains no olivine) the norm implies the presence of 12% olivine.

Spinel

This may occur in either one or both of the following forms (i) euhedral crystals in plagioclase; (ii) anhedral grains in aggregates of the mafic minerals. Optical and X-ray examination have not shown any difference in the composition of the two forms of spinel.

Discussion

There are obvious textural, mineralogical and chemical differences between the marginal and central portions of the metagabbro body see Table 4). These differences may be of primary igneous origin, or they may represent a response to later granulite facies metamorphism.

Textural features

The textural variations described above show that the coarse-grained facies of the centre has retained an essentially igneous texture. Nearer to the marginal facies the texture cannot be distinguished from that of surrounding granulites. We consider that this variation reflects an increasing degree of recrystallization of the gabbro in response to the thermal and mechanical effects of metamorphism. The recrystallization of the marginal facies would have been aided by an initial fine grain size, such as is normal in a chilled margin.

Significance of olivine in the metagabbro

Analyses show that all rocks in the metagabbro are undersaturated with respect to silica. The composition probably represents a close approximation to the gabbroic magma. The silica-undersaturation is reflected in the development of low silica mineral phases such as olivine, kaersutitic amphibole and spinel.

Olivine is absent however, from the marginal facies, even though chemical analysis of the rock shows that it could have been an important phase. A possible explanation is that recrystallization of the marginal facies involved a degree of tectonic granulation whereby olivine became an unstable component and was replaced by an amphibole with comparable low content of silica. Under these circumstances the presence of olivine in the central coarse-grained facies could indicate that this portion of the body has been unaffected by the tectonic granulation which may have accompanied metamorphism.

Presence of volatile components

Calcite appears to be concentrated in clots of granular amphibole within otherwise unrecrystallized gabbro. The retention of calcite as well as of the hydroxyl of amphibole during metamorphism is favoured by high temperature and relatively high confining pressure.

Under these conditions patchy concentration of volatile components appears to have controlled similar patchy development of clots of carbonate and amphibole. It is suspected that the patchy concentrations of volatile components in the metagabbro represent concentrations of end-phase material from the crystallization of the gabbro. During recrystallization of the gabbro these volatile-rich domains have enabled "wet metamorphic clots" to develop in these sites.

Solid-state-diffusion and reaction phenomena

There is evidence to suggest that considerable movement of chemical components has taken place in the solid state within the rocks of the coarse-grained facies.

Variation of 2V within individual augite grains in Spec. 16311 implies variation in their composition. The $2V_\gamma$ of the augite is lower around included olivine grains (42°) and higher around included plagioclase (57°) than the normal value (49°) (see Fig. 3). This suggests a marked increase in the calcium content of the augite adjacent to plagioclase, and a corresponding decrease in calcium content adjacent to olivine thus confirming some metamorphic redistribution of calcium in the rock.

A further example of solid state diffusion is that spinel inclusions in labradorite are surrounded by "haloes" of andesine. The original Ca-rich plagioclase of the gabbro was converted to a more Na-rich variety during metamorphism, thus releasing aluminium. Aluminium has been fixed as spinel within the plagioclase grains by

TABLE 4

Chemical analyses, modes and norms of some Fraser Range metagabbros.

		16307	16309	16311		24522W
SPECIFIC GRAVITY		3.03	3.08	3.12		3.10
				(*a*)	(*b*)	
MODAL%	Plag.	48	45	33	20	31
	OPx	23	24			
	CPx	10	13	}31	}56	} 42
	Hbe	17	16	22	9	18
	Olivine	nil	trace	7	9	3
	Spinel	trace	1	7	6	5
	Opaques	2	1	tr.	tr.	1
OXIDE%	SiO_2	49.23		45.88		48.03
	TiO_2	0.70		0.60		1.08
	Al_2O_3	14.63		10.51		14.56
	Fe_2O_3	2.49		2.37		1.76
	FeO	10.12		10.46		10.08
	MnO	tr.		tr.		0.24
	MgO	11.29		19.15		12.57
	CaO	8.85		7.50		9.04
	Na_2O	2.15		1.80		1.69
	K_2O	0.43		0.56		0.41
	P_2O_5	0.04		0.15		0.23
	H_2O^+	0.40		0.86		0.34
	H_2O^-	0.04		0.05		0.22
		100.37		99.89		100.25
NORMATIVE%	Or	2.56		3.28		2.42
	Ab	18.20		15.21		14.30
	An	28.99		18.97		30.94
Di	Wo	6.12		7.18		5.18
	En	3.74		4.96		3.24
	Fs	2.05		1.64		1.63
Hyp	En	13.88		4.10		15.24
	Of	7.59		1.42		7.65
Ol	Fo	7.36		27.09		8.99
	Fa	4.42		10.19		4.97
	Mag	3.61		3.43		2.55
	Il	1.34		1.14		2.05
	Ap	0.10		0.37		0.55

magnesium which has diffused through the plagioclase from nearby olivine. Once nucleated, spinel crystals appear to have continued to grow, thus producing prominent haloes of andesine around the spinel. The expelled calcium appears to have been used to produce augite or amphibole outside the plagioclase grains.

Concentration of spinel along some grain boundaries, particularly those separating plagioclase and hypersthene, has resulted from limited reaction between these two minerals to form spinel and clinopyroxene, as shown in Figure 4.

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The field work, initial petrographic studies and analysis of Spec. 24522W were done by A. F. Wilson with facilities of the University of Western Australia, 1952-1959. Later petrographic studies and the other chemical analyses were done at the University of Queensland by D. D. Middleton.

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